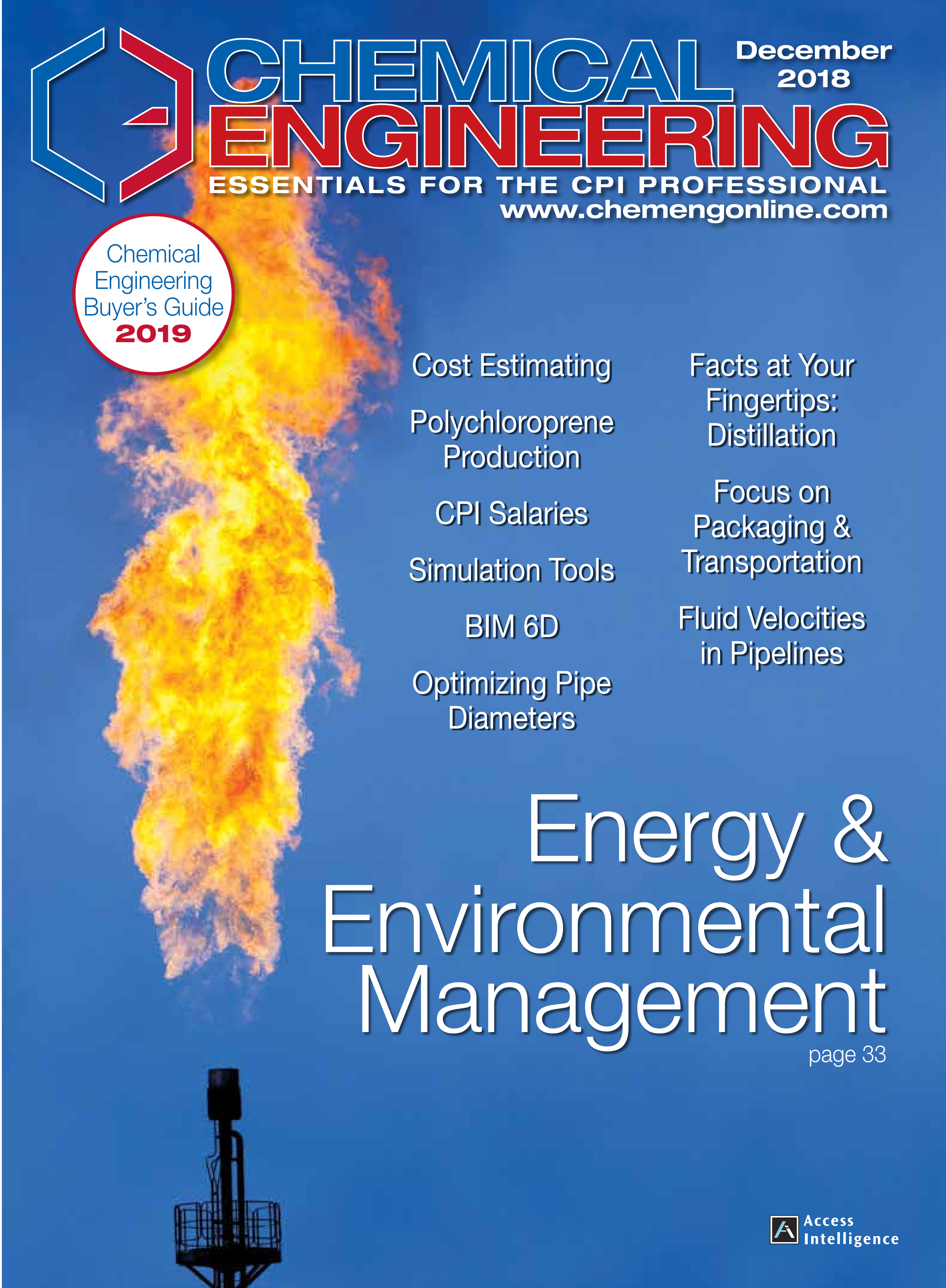

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December 2018

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page 33

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December 2018 Volume 125 | no. 12

Cover Story

33

In the News

13

18

44

Technical and Practical

56

23

28

Equipment and Services

Departments

Advertisers

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Editor's Page

Keeping up with automation

Last month, news broadcasts announced that an artificial intelligence (AI) news anchor, said to be the world's first ever, had gone live in China.[1] The AI anchor was modeled after a real-life news presenter, and is said to be learning from live broadcasting videos. The news, as I watched it on television, was accompanied by somewhat anxious-sounding jokes about how, in the future, AI broadcasters might replace the very newscasters who were presenting this story.

While there are numerous concerns about advanced technologies like AI, the fear of job loss, sometimes guised in jokes about "robots taking our jobs," seems to be the most widespread concern.

The job outlook

Some analysts who predict the effects of the current boom in automation offer a gloomy outlook for future jobs, while others take a more positive view and say that even though jobs will be lost, new jobs that require new skills will be created. Historically, the creation of new jobs after major technological advances, such as in agriculture and manufacturing, offer a precedent for this more positive line of thinking. Some advisors, such as Gartner (www.gartner.com), are even more optimistic and say that technologies like AI will create more jobs than they eliminate.[2]

All analysts, however, seem to agree on one outcome of the current technological boom — that many will need to learn new skills to fill future jobs. A rather comprehensive report on this topic is one titled "Jobs lost, jobs gained: What the future of work will mean for jobs, skills, and wages,"by McKinsey & Company (www.mckinsey.com).[3] In its report, McKinsey states that "Our key finding is that while there may be enough work to maintain full employment to 2030 under most scenarios, the transitions will be very challenging. . ."

CPI outlook

The McKinsey report says that some of the job categories with the highest percentage of job growth include professionals such as engineers and scientists. And, our Newsfront this month, "Economy and Opportunity Drive High CPI Salaries," (pp. 13–16) outlines a very positive outlook for chemical engineering jobs in the future. It also discusses some of the changes that are occurring in the field and initiatives that are being taken to prepare future engineers. The U.S. National Academies of Sciences, Engineering and Medicine (NAS), for example, is currently making plans to study and report on the changes expected in the chemical engineering profession, including those involving topics such as advanced computing, analytics, machine learning and AI.

Keeping up with the trends

Keeping up-to-date with the rapidly changing, digitalized landscape is challenging. *Chemical Engineering* strives to help in that endeavor by covering new technologies in each issue and on our website. Our Connected Plant Conference in February (www.connectedplantconference.com) also offers an opportunity to learn about current trends and meet others on the path to digitalization. We look forward to seeing you there. ■

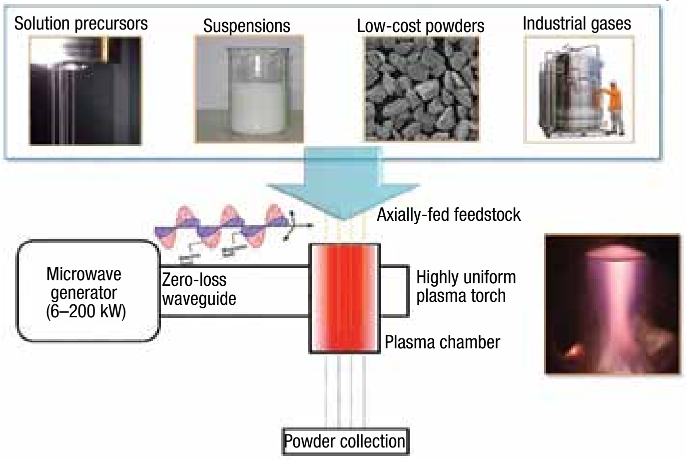
Dorothy Lozowski, Editorial Director

1. www.cnbc.com/2018/11/09/the-worlds-first-ai-news-anchor-has-gone-live-in-china.html
2. www.gartner.com/newsroom/id/3837763
3. www.mckinsey.com/featured-insights/future-of-work/jobs-lost-jobs-gained-what-the-future-of-work-will-mean-for-jobs-skills-and-wages

Microwave-plasma platform engineers solid-material properties

Edited by:
Gerald Ondrey

Amastan Technologies



A new production process for engineering a range of nano- and microstructured solid materials can reduce the costs of manufacturing the materials compared to conventional "wet-chemistry" approaches, and can allow novel chemistries that are not accessible through traditional methods. Developer Amastan Technologies (North Andover, Mass.; www.amastan.com) has built two production-scale plasma reactors and plans to launch its first commercial products — metal powders designed for 3-D printing — in 2019.

The technology platform, known as Uni-Melt (diagram), concentrates microwave energy inside the reactor to produce a highly uniform, 6,000K plasma region for synthesis of solid particles. Raw materials, in the form of solution precursors or raw solids, are fed into the reactor in a continuous process using a carrier gas. By carefully and precisely controlling a set of 15 process parameters, the system can guide the formation of a range of engineered solid materials with various properties. The controlled parameters include plasma power, residence time and flow gas, which can create oxidizing, reducing or neutral environments for synthesis.

"The Uni-Melt platform is highly versatile, with the ability to create dense metal powder with spherical morphology, such as those required for 3-D printing, as well as pure crystal structures with defined stoichiometry, such as those required for catalysts or cathode powders," says Amastan CEO Aaron Bent. The platform can also be used to create high-surface-area materials, nanostructured surfaces and materials with extremely tight particle size distributions, he says.

"By carrying out the synthesis using plasma, it is possible to eliminate multi-step batch processes that generate sizeable levels of waste," Bent explains. "And the ions and radical species in the plasma offer the opportunity to access chemical routes that would not be attainable with wet-chemistry approaches."

After the 3-D printing metal powders, Amastan plans to commercialize cathode powders for advanced battery applications.

Progress toward using ammonia as a hydrogen carrier for fuel cells

In order for ammonia to serve as a hydrogen carrier, it is necessary to develop separation techniques that can reliably recover H_2 from the decomposition of NH_3 with sufficient purity for operating proton-exchange membrane (PEM) fuel cells. A step in this direction has been achieved by a Japanese collaboration lead by Yoshitsugu Kojima at Hiroshima University (Hiroshima; www.hiroshima-u.ac.jp), in collaboration with Taiyo Nippon Sanso Corp., Toyota Motor Corp. and Showa Denko K.K. The researchers, with support from a cross-ministerial strategic innovation program (SIP), named "Energy Carrier," have developed components needed to decompose NH_3 and recover high-purity H_2.

Using a ruthenium catalyst supported on MgO, NH_3 is decomposed in a microchannel cracker into H_2 and N_2 at 500°C and 0.1 MPa, with a 99.8% conversion efficiency. The remaining NH_3 concentration is reduced from 1,000 parts per million (ppm) to below 0.02 ppm using a combination of pressure-swing adsorption and a zeolite-packed absorption column, to produce H_2 with 99.98% purity (NH_3 <0.02 ppm, N_2 <10 ppm). A net H_2 recovery rate of 90% was achieved. By utilizing the heat from the cracking, a net energy efficiency of 80% was observed.

The researchers believe the technology can be scaled up from the present 10-Nm^3/h scale to 300–1,000 Nm^3/h for commercial applications, such as fuel-cell-powered cars and forklifts.

COMMERCIAL DEBUT

The world's first commercial plant based on the patented PLA*neo* technology of thyssenkrupp Industrial Solutions AG (Essen, Germany; www.thyssenkrupp-industrial-solutions.com) recently started production in Changchun, China. Operated by the Jilin COFCO Biomaterial Corp., the new plant produces all standard polylactide (PLA) types, for the production of eco-friendly packaging, fibers, textiles and engineering plastics.

PLA is a 100% bio-based and compostable plastic that can replace conventional petroleum-based polymers in many areas of application. Developed by thyssenkrupp subsidiary Uhde Inventa-Fischer, the PLA*neo* technology converts lactic acid into PLA in a particularly efficient and resource-friendly way (for more details, see *Chem. Eng.*, February 2017, p. 8).

F-T CATALYST

Researchers from the National Institute of Clean-and-Low-Carbon Energy (Beijing, China; www.nicenergy.com) and Eindhoven University of Technology (TUE; the Netherlands; www.tue.nl) have developed an iron-based Fischer-Tropsch (F-T) catalyst that exhibits a very low selectivity for producing carbon dioxide. That means the production of fuels by coal-to-liquids (CTL) processes may become more productive and less costly, since conventional Fe-based F-T catalysts typically convert 30% of the CO feed into byproduct CO_2. Although cobalt-based F-T catalysts have a similar CO_2 selectivity, Co is more expensive and less tolerant to sulfur, which has made Fe-based F-T the preferred route for

(Continues on p. 6)

CTL processes.

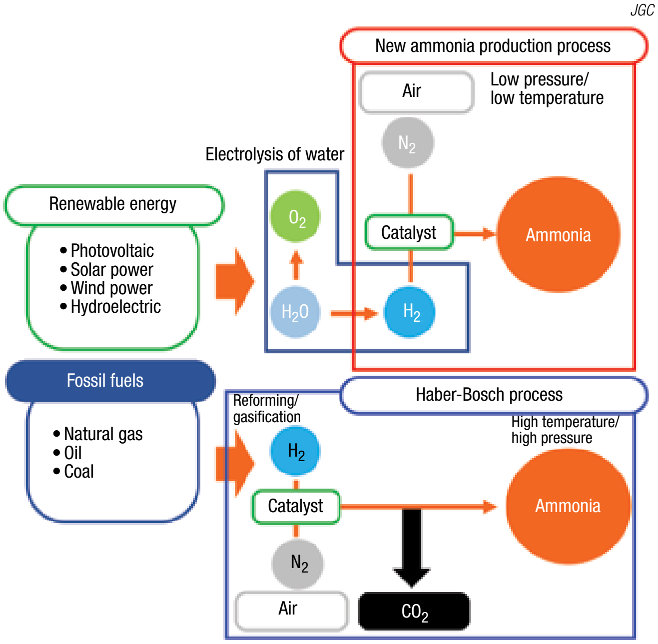
By eliminating CO_2 production in the F-T step, all of the CO_2 produced by a CTL process takes place in the water-gas-shift (WGS) reactor, thereby generating a concentrated CO_2 stream, which is important for carbon-capture and storage or utilization strategies, according to the researchers, who reported their findings last month in *Science Advances*.

The Sino-Dutch research team discovered that the CO_2 released in the F-T synthesis is caused by the fact that the Fe-based catalysts are not pure, but consist of several components. They were able to produce a pure form of epsilon iron carbide, which has a very low CO_2 selectivity. Although the existence of ε(')-Fe_2C had already been known, the material had not been stable enough for the harsh conditions used in the F-T synthesis. The Sino-Dutch research team has now shown that this instability is caused by impurities in the catalyst. The phase-pure ε(')-Fe_2C is said to be stable and remains functional, even under typical industrial process conditions (23 bars and 250°C).

By eliminating nearly all CO_2 generated in the F-T reactor, less energy is required, which reduces operating costs by roughly €25 million/yr for a typical CTL plant, according to TUE.

(Continues on p. 9)

Ammonia synthesized from renewable power and hydrogen



A collaboration between JGC Corp. (JGC, Yokohama, Japan; www.jgc.com), the National Institute of Advanced Industrial Science and Technology (AIST), the National Institute of Technology, Numazu College, and JGC's subsidiary, JGC Catalysts & Chemicals Ltd., (JGC Group), under the auspices of the cross ministerial strategic innovation promotion program (SIP),"Energy Carriers," announced that its joint study has resulted in the world's first success in the synthesis of NH_3 using H_2 produced through the electrolysis of water by renewable energy, and generation of electricity through gas turbines fueled by synthesized NH_3.

Last May, JGC Group achieved success in development of a new ruthenium catalyst supported by rare earth oxide (Ru/REO_2), which is capable of efficiently synthesizing ammonia at a low (300–400°C) temperature and low pressure (5–8 MPa), which is far milder than the 400–500°C and 14–30 MPa used for an iron-based Haber-Bosch process. The REO-supported Ru catalyst is said to have "excellent stability" compared to Ru catalysts that utilize carbon-based carriers. JGC began operating a demonstration plant — located at Fukushima Renewable Energy Institute, AIST in Koriyama City, Fukushima Prefecture — that is capable of producing 20 kg/d of NH_3. Initial testing of the new catalyst used high-purity hydrogen from gas cylinders.

JGC Group has verified the ability of handling rapid changes in operational conditions when using renewable energy. Now, the group has replaced the bottled H_2 supply with H_2 generated by solar-powered water electrolysis to make ammonia, which then fueled a gas turbine to generate electric power (47 kW).

This is claimed to be the first time renewable H_2 has been used to make NH_3 that is subsequently used for CO_2-free power generation. The achievement is a step toward the vision promoted by SIP Energy Carriers research of "Japan creating an innovative low-carbon, hydrogen-fueled economy and taking the lead in hydrogen-related industries on the world market" by the year 2030.

MOF-coated mesh membranes separate oil from water

Current oil-water separation technologies, such as centrifugation, filtration, dissolved air flotation, distillation, oil skinners, adsorption and electrochemical methods, are of low efficiency and consume a lot of energy during complex separation processes. Mesh membranes have attracted much interest lately, and some polymers have been successfully applied onto mesh membranes. However, due to their oleophilic properties, the surfaces of those membranes are easily polluted or even blocked by oil.

Now, a ZIF-8-coated mesh membrane for high-efficiency oil-water separation has been prepared by a team from Jilin University (Changchun, China; www.jlu.edu.cn) and Sinopec Institute of Safety Engineering (Qingdao, China; www.sinopec.com). ZIFs — zeolite imidazole frameworks — are a subfamily of metal organic frameworks (MOFs) that exhibit various topologies and morphologies, and are chemically and thermally fairly stable.

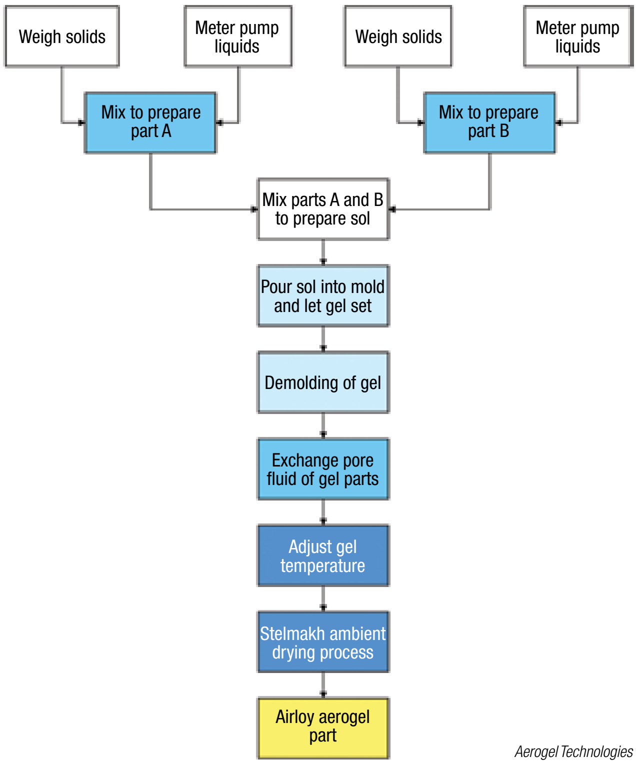
The membranes have micro- and nano-scale architectures, and are fabricated by simply immersing mesh into a precursor solution at room temperature and atmospheric pressure. Water molecules are imbibed into a rough solid surface to form a barrier layer that produces a strong repulsive force to an oil droplet, which makes the membranes exhibit underwater superoleophobicity. The membranes are also highly stable at high temperatures and after exposure to various organic solvents. Due to its facile fabrication, the membrane can be easily enlarged, which is critical for oil-water separation.

According to the team, the ZIF-8 coated mesh membranes exhibit high water flux (10.2×10^4 L/m^2/h) and achieve a separation efficiency better than 99.99% for various oil-water mixtures, with the residual oil content in the collected water less than 4 ppm.

Mechanically strong aerogels get closer to commercialization

Aerogels — ultralight, insulating and heat-resistant nanoporous solids — offer benefits in many applications, but commercially available aerogels are typically limited to just two formats: particles and blankets. Aerogel Technologies, LLC (Boston, Mass.; www.aerogeltechnologies.com) is currently constructing a pilot plant in Boston to manufacture new, mechanically strong shaped-form aerogels in film and panel formats. In the past, aerogels were traditionally brittle and easily crushed, but these new forms boast durability similar to plastics, explains Stephen Steiner, president and CEO of Aerogel Technologies. "For the first time, we have commercially available aerogels that can be used as a multifunctional lightweight alternative to structural plastics. They are thermally insulating, soundproofing and can handle high temperatures," adds Steiner. Not only are the aerogels lighter and more insulating than plastics and foams, they are also extremely insulative against noise, are non-flammable and are machinable, which means they can be processed similarly to engineering plastics.

The new pilot plant — due to begin operating in May 2019 — is well-suited for large-scale aerogel production since Aerogel Technologies' process eliminates the costly supercritical drying step typically required for large aerogel parts, says Steiner. Supercritical dryers are readily used in producing aerogel particles and blankets, but they pose a problem in producing more substantial monolithic forms, since the dryers would need to be prohibitively large to accommodate the parts. Removing the supercritical dryer not only lowers costs by enabling operation at ambient conditions, but it also provides for a smaller equipment footprint, which means that several process units can operate in parallel in a manufacturing facility, making the process modular and easily expandable. Initially, says Steiner, the pilot plant will focus on 1- and 4-ft panel sizes, but these dimensions could be widely expanded to meet customer needs.



Aerogel Technologies

Advanced facility accelerates commercial development of nanoscale materials

Flame-spray pyrolysis (FSP) is a type of aerosol synthesis in which solid particles condense from the vapor phase after the combustion of droplets of solution. FSP has been used to produce industrially important nanoscale solids, such as fumed silica, alloy powders, metallic oxides, carbon black and others. However, FSP is limited practically to systems of one atom type because processes can only be optimized for a single crystal phase.

"The more atomic species that are involved, the more complex and difficult it is to get the exact crystal structure sought after in flame condensation process," says Joe Libera, a research leader at Argonne National Laboratory (Lemont, Ill.; www.anl.gov). Libera and colleagues at Argonne's Combustion Synthesis Research Facility have developed an FSP system that employs an array of instrumentation to gain insight into how solid particles form during the FSP process.

"In FSP, the condensation of solids happens very quickly and over short distances," Libera says, "so characterizing how that occurs allows us to begin to control the properties of the resulting materials," including crystallinity, particle size and shape, surface area, dopant concentration and others. The researchers are building a database of material outcomes based on different FSP process conditions, and are applying machine-learning approaches to arrive at non-intuitive insights, Libera says.

The Argonne FSP system is equipped with laser diagnostics to measure flame properties and spectroscopic and other instruments for measuring temperature, particle size and chemical species. The information will be used to accelerate process development for a wider range of multi-atom materials synthesized by flame-spray pyrolysis at commercial scales.

With funding from the U.S. Dept. of Energy, Libera's group is working with engineers from Cabot Corp. (Boston, Mass.; www.cabotcorp.com) on using FSP to make next-generation cathode powders and the solid electrolyte material lithium lanthanum zirconium oxide (LLZO) for battery applications. The Argonne FSP facility is open to industrial companies, who can use it to develop new nanomaterials.

A solar-powered electrolysis process extracts lithium from seawater

Today, all commercial lithium is sourced from ores or brines on land, where the total lithium reserves amount to 14 million tons. In contrast, the oceans contain 230 billion tons of lithium, although the lithium concentration in seawater is very low — 0.1 to 0.2 parts per million (ppm). Several methods have been proposed for extracting lithium compounds from seawater, including adsorption- and dialysis-based methods, but the lithium extraction rates by the current techniques are relatively low. Now, researchers from Nanjing University (Nanjing, China; www.nju.edu.cn) have developed a solar-powered electrolysis process to extract lithium from seawater that is said to be faster and more controllable than the current methods, and that it could overcome the limit of the concentration difference present in the dialysis method.

The Nanjing team used a lithium superionic conductor Nasicon-type solid-state electrolyte as the Li^+-selective membrane, with an aprotic electrolyte instead of an aqueous solution in the anode side of the electrolysis cell to create a proton-free compartment. The prototype device can be powered by a solar panel.

The electrolyte is divided into two parts by the solid-state electrolyte. A lithium-perchlorate ($LiClO_4$)/propylene-carbonate solution is on the cathode side and seawater is on the anode side. Cations in seawater move from the anode toward the Li^+-selective membrane, but only lithium ions are transported to the cathode. The other cations are blocked and remain in the anode compartment.

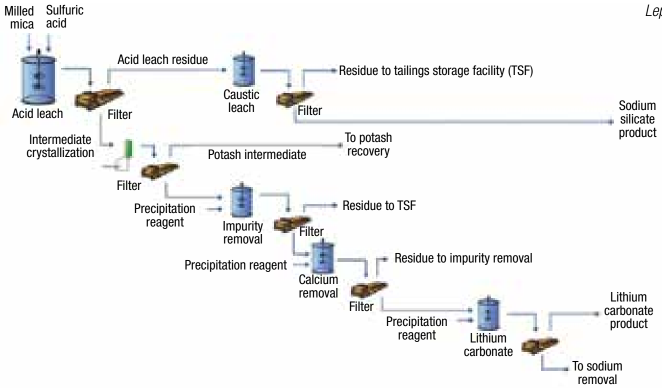
On the cathode side, lithium ions are reduced to metallic lithium on a copper foil. Chloride (Cl^-) or hydroxide (OH^-) ions are oxidized into chlorine or oxygen gas on the anode side. Some of the Cl_2 gas may further react with water to form hypochlorite, according to the researchers.

NITROGEN FIXATION

Researchers from the École Polytechnique Fédérale de Lausanne (EPFL; Switzerland; www.epfl.ch) have developed a uranium-based complex that allows nitrogen fixation reactions to take place at ambient conditions. The work lays the foundation to develop new processes for synthesizing nitrogen products, such as cyanamide, a compound that is widely used in agriculture, pharmaceuticals, and various organic compounds.

Last year, the laboratory of EPFL's Marinella Mazzanti was able to convert molecular nitrogen into ammonia at ambient conditions by synthesizing a compound containing two uranium (III) ions and three potassium centers held together by a nitride group (*Chem. Eng.,* September 2017, p. 8). Now, the group, in collaboration with other EPFL groups, has shown that by replacing the nitride bridge in the uranium system with an oxo bridge, they can still bind N_2. In addition, the bound dinitrogen can be easily cleaved at ambient conditions by carbon monoxide to make cyanamide. The reactivity of the oxo-bridged dinitrogen complex was said to be remarkably different compared to the previous nitride complex and the few other nitrogen complexes known in the field. The research is described in a November 2018 issue of *Nature Chemistry*. ❑

New process taps into lithium-bearing micas



Lepidico

The increased demand for lithium in recent years — driven mainly by battery manufacturing — has broadened the scope of lithium-processing technologies. Typically, lithium is mined from spodumene ore or sourced from brine deposits, but a new process enables lithium's recovery from mica minerals — a typically overlooked raw material. Lepidico (Perth, Western Australia; www.lepidico.com) is currently in the process of scaling up its L-Max technology (see diagram) for processing lithium-bearing micas and phosphate minerals. What sets L-Max apart, according to Joe Walsh, Lepidico's managing director, is its proprietary impurity-removal steps, which result in several salable byproducts and very little waste. "A number of those impurity removal stages, for instance, the removal of potassium, result in a byproduct. We've tried to add as much value as we can by producing salable materials as we step through the process," says Walsh.

L-Max begins with a relatively conventional sulfuric-acid leach followed by crystallization and subsequent filtration and purification steps, finally resulting in the precipitation of lithium carbonate. Walsh points out that the process is particularly adept at handling potentially problematic impurities, especially fluorine. "The fluorine stays in solution until a certain pH range is reached, at which point a benign compound, aluminum fluoride, is formed. This makes it the most sustainable and promising mica-based process technology in terms of its health and safety attributes," adds Walsh.

The L-Max process has undergone mini-plant trials operating at 1–1.5 kg/h, with continuous closed-loop operation for about a week at a time. The team is currently constructing a 15-kg/h pilot plant, located in Perth, which is set to be commissioned in April 2019. Concurrently, feasibility studies are underway for a larger "Phase 1" plant, which will be designed to produce around 5,000 metric tons/yr of lithium carbonate. Lepidico is considering locations in Ontario, Canada for the Phase 1 plant. ■

Business News

Plant Watch

Synthomer opens expanded nitrile latex production facility in Malaysia

November 13, 2018 — Synthomer (London, U.K.; www.synthomer.com) opened its expanded nitrile latex production facility in Pasir Gudang, Malaysia. This $63.5-million project added 90,000 metric tons per year (m.t./yr) of capacity, and is the first of two planned expansion phases at the site using a new reactor technology. The second phase, adding a further 60,000 m.t./yr of nitrile latex capacity, is slated to come online in 2020.

Showa Denko completes expansion of nanoparticle TiO_2 plant

November 12, 2018 — Showa Denko KK (SDK; Tokyo; www.sdk.co.jp) has completed a capacity expansion for nanoparticle titanium oxide (TiO_2) used in the production of multilayer ceramic capacitors (MLCCs). At Showa Denko Ceramics' plant in Toyama Prefecture, Japan, the new production line will increase capacity by 30%.

DuPont to build a new specialty materials manufacturing plant in East China

November 8, 2018 — DuPont (Wilmington, Del.; www.dupont.com) is investing more than $80 million to build a new manufacturing facility in Zhangjiagang, Jiangsu Province, in East China. The new facility will produce compounded engineering plastics and adhesives for transportation, electronics and industrial and consumer products. The site is expected to become operational in 2020 with expansion through 2023.

Praxair to build a new liquid hydrogen plant in La Porte

November 7, 2018 — Praxair, Inc. (Danbury, Conn.; www.praxair.com) has commenced construction of its fifth liquid hydrogen plant in the U.S., located in La Porte, Tex. Praxair's new plant, scheduled to start up in 2021, will produce over 30 ton/d of high-purity liquid hydrogen. It will be integrated with the recently constructed air separation plant in La Porte.

Nippon Shokubai to build a new acrylic acid plant in Indonesia

October 31, 2018 — Nippon Shokubai Co. (Osaka, Japan; www.shokubai.co.jp) plans to build a $200-million acrylic acid (AA) production unit with a capacity of 100,000 m.t./yr, which will bring the company's total AA production up to 240,000 m.t./yr. The new AA plant will be located at an existing site in Cilegon, Indonesia. Mechanical completion of the new unit is slated for March 2021, with commercial operations expected to begin in November 2021.

Solvay to increase fluorelastomer production in China and Italy

October 29, 2018 — Solvay S.A. (Brussels, Belgium; www.solvay.com) is set to increase the company's fluoroelastomer (FKM) production with the recent addition of a new FKM plant in Changshu, China, as well as the implementation of production expansions for specific FKM peroxide-curable and bisphenolic terpolymer grades at Solvay's sites in Changshu and Spinetta Marengo, Italy. The combined production capacity will be expanded by 30% before the end of 2019.

Lanxess increases production volume of micronized iron-oxide red pigments

October 29, 2018 — Lanxess AG (Cologne, Germany; www.lanxess.com) implemented targeted debottlenecking at its Krefeld-Uerdingen, Germany, site to increase the product availability of its Bayferrox and Colortherm micronized iron-oxide red pigments by more than 5,000 m.t./yr.

Mergers & Acquisitions

Standard Lithium signs JV term sheet with Lanxess

November 12, 2018 — Standard Lithium Ltd. (Vancouver, B.C.; www.standardlithium.com) has signed a term sheet with Lanxess for a planned joint venture (JV) in the commercial production of battery-grade lithium from brine extracted from the Smackover Formation in South Arkansas. Under the proposed terms of the JV, Lanxess would contribute lithium extraction rights and Standard Lithium would contribute the pilot plant being developed on the property, as well as its proprietary extraction processes.

DuPont sells Iowa-based cellulosic ethanol plant to Verbio

November 12, 2018 — DuPont Industrial Biosciences and Verbio North America Corp. (VNA), a subsidiary of German bioenergy producer Verbio Vereinigte BioEnergie AG, have reached terms for VNA to acquire DuPont's cellulosic ethanol plant in Nevada, Iowa. VNA intends to install facilities to produce renewable natural gas from corn stover and other cellulosic crop residues at the site.

Evonik acquires PeroxyChem for $625 million

November 8, 2018 — Evonik Industries AG (Essen, Germany; www.evonik.com) plans to acquire PeroxyChem LLC (Philadelphia, Pa.; www.peroxychem.com) from One Equity Partners for $625 million. PeroxyChem is a manufacturer of hydrogen peroxide and peracetic acid. The transaction is scheduled to be completed by mid-2019.

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Orion Engineered Carbons acquires acetlyene carbon black business

November 6, 2018 — Orion Engineered Carbons S.A. (Luxembourg; www.orioncarbons.com) acquired Société du Noir d'Acétylène de l'Aubette, SAS (SN2A), a manufacturer of acetylene carbon black, from LyondellBasell (Rotterdam, the Netherlands; www.lyondellbasell.com) and its French affiliate. SN2A is headquartered in Berre l'Etang, France. Acetylene carbon black is an ultra-pure material distinguished by its high electrical and thermal conductivity.

Neste and Clariant announce joint sustainability initiative

November 6, 2018 — Neste Corp. (Espoo, Finland; www.neste.com) and Clariant (Muttenz, Switzerland; www.clariant.com) joined forces in developing new sustainable material solutions accessible to a variety of industries. In the first phase of the partnership, the companies will start replacing fossil-based ethylene and propylene used in Clariant's hot-melt adhesives with monomers derived from renewable feedstock.

Air Products to acquire GE's gasification business and technology

November 5, 2018 — Air Products (Lehigh Valley, Pa.; www.airproducts.com) agreed to acquire GE's gasification business, allowing Air Products to expand its syngas solutions portfolio and its presence in gasification projects worldwide. The gasification business being acquired by Air Products includes GE's share of its 50/50 JV with China Shenhua Coal to Liquid and Chemical Co.

Arkema acquires adhesives manufacturer in Spain

November 1, 2018 — Arkema (Colombes, France; www.arkema.com) has acquired Afinitica, a Spanish company specializing in instant adhesives, also known as cyanoacrylates. This acquisition will enable Arkema's Bostik brand to develop a solid position in adhesives used in markets with strong growth potential, including electronics and medical equipment.

Lonza sells its Water Care business for $630 million

November 1, 2018 — Lonza Group (Basel, Switzerland; www.lonza.com) announced that Platinum Equity will acquire Lonza's Water Care business for $630 million. Based in Alpharetta, Ga., Water Care has six manufacturing facilities in key regions, including North America, South America and South Africa. The agreement is expected to close in the first quarter of 2019.

Jacobs to sell Energy, Chemicals and Resources business to WorleyParsons

October 21, 2018 — Jacobs Engineering Group Inc. (Dallas, Tex.; www.jacobs.com) agreed to sell its Energy, Chemicals and Resources (ECR) segment to WorleyParsons Ltd. (North Syndey, Australia; www.worleyparsons.com) for $3.3 billion. Following the completion of the transaction, Jacobs will be focused solely on two lines of business: Aerospace, Technology, Environmental & Nuclear (ATEN); and Buildings, Infrastructure & Advanced Facilities (BIAF). ■

Mary Page Bailey

Economy and Opportunity Drive High CPI Salaries

Amid a tight labor market, CPI workers at all levels are in high demand as the range of jobs requiring chemical engineering expertise becomes increasingly diverse

IN BRIEF

COMPETITIVE LABOR MARKET

EXPANDING CAREER SCOPE

ESTABLISHING FUTURE DIRECTIONS

EVOLVING EDUCATION APPROACHES

RECENT CPI SALARY DATA

FIGURE 1. Recent data collected suggest that chemical engineering salaries remain high, especially for experienced chemical engineers, and unemployment remains low

Many current indicators suggest that it is a great time to be working in the chemical process industries (CPI). Those with chemical engineering degrees are in high demand, and the salaries reported by working engineers generally reflect that demand (see box, p. 14). At the same time, opportunities for careers are growing as the field evolves. The unemployment rate for chemical engineers remains low (~1.5%), as it has been in recent years and is lower than the overall unemployment rate for all fields, which dropped to 3.7% in October 2018, according to the U.S. Bureau of Labor Statistics (BLS; Washington, D.C.; www.bls.gov).

Competitive labor market

For the past several years, much has been reported about several long-term workforce issues, including a large number of retirements of workers from the "Baby Boom Generation" and a skills gap in many manufacturing sectors, including the CPI. These trends, along with other factors, such as a capital spending boom spurred by inexpensive shale gas in the U.S., have created an ongoing tight market for workers in the CPI. Now, recent factors such as broad economic growth in the U.S. and low overall unemployment, have put additional pressure on the labor market for CPI workers, both degreed engineers and non-degreed skilled workers.

"We are all facing a competition for talent in an environment where there is a decreasing supply for workers amidst an increasing demand," says Luciana de Oliveira Amaro, BASF vice president for talent development and strategy in North America. "For the manufacturing economy specifically, the U.S. already struggles with shortfalls in manufacturing talent. By 2030, this deficit is set to reach a shortfall of 383,000 workers." These workforce-related challenges are shared by all companies operating in the U.S., she says.

In October 2018, results from the Manufacturers' Outlook Survey, conducted by the National Association of Manufacturers (NAM; Washington, D.C.; www.nam.org) showed high levels of optimism among manufacturing companies in several sectors, including the CPI. However, the survey also suggests that the inability to attract and retain workers remained the top concern for respondents, with 73.2% of survey takers rating it as their most pressing concern. The survey also found that nearly half of manufacturers (45.4%) cite the skills-gap crisis as the number one threat facing their business.

The need to attract future workers is broadly understood among CPI companies,

BASF's Amaro says, and a raft of policies and programs to encourage students to choose careers in science, technology, engineering and mathematics (STEM) have emerged. The burgeoning network of partnerships among industry players, such as BASF, and federal and local governments, along with educational institutions, "makes us optimistic about the future of our workforce development," Amaro comments.

Further assessing the overall CPI workforce situation, Amaro explains that the two factors of Baby Boomer retirements and capital expansion have affected the labor pools for both bachelors-degree-holding engineers and skilled, non-degree trade workers and operators equally. "On the other hand, there is an important difference: since the 1980s, the U.S. has had a push to make every student college-ready before graduating high school," Amaro says, leading to an oversupply of four-year degree holders in almost all areas and a lack of focus on middle-skill jobs from primary and secondary education. "This shift helped create a talent pipeline that could not support the middle-skill jobs that our industry and many others need to succeed," she says.

RECENT CPI SALARY DATA

Generally speaking, salaries for those holding chemical engineering degrees have been among the highest across all fields for years, and the current data show all the signs of maintaining those high levels. There are several factors exerting upward pressure on salaries, including a competitive labor market, low unemployment and a growing number of positions requiring chemical engineering expertise.

A recent survey (October 2018) of CPI professionals conducted by *Chemical Engineering* found that in 2018, the average salary of respondents was \$133,600, a 1.6% increase over the average from a similar survey in 2017, and 2.0% higher than in 2016. The survey also found that over 75% of respondents earned a salary greater than \$100,000 annually, with 34.7% of all respondents having salaries between \$100,000 and \$140,000 per year. Only 12% earned less than \$80,000 per year. However, the respondent population for the *CE* survey did skew toward higher experience levels, with 70% reporting more than 15 years of experience. Since engineers with experience tended to report higher salaries, the average is likely somewhat higher than the overall chemical engineering population. For example, the U.S. Bureau of Labor Statistics (BLS) reported the average salary for chemical engineers as \$102,160 in 2017, and, in its biannual salary survey in 2017, the American Institute of Chemical Engineers (AIChE; New York, N.Y.; www.aiche.org) reported a median salary for chemical engineers of \$124,000. The AIChE total was unexpectedly lower than the previous survey in 2015, but the organization said the slight decrease had more to do with changes in survey methodology than an actual decrease in salaries.

In the current 2018 *CE* survey, the salary average among respondents who worked for chemical manufacturing companies was the highest of all employer types, at just over \$136,000. The average salary of respondents who worked at engineering, procurement and construction (EPC) firms was \$131,150, and for equipment vendors, the average was \$127,400. Self-employed consultants averaged \$123,000, although the sample size was small.

Also, *CE* survey takers were asked if they anticipated higher engineering-related salary in 2018 than in the previous year, and the majority (56.7%) said they expected a higher salary, while 37.8% said it would likely be the same. Only 5.5% anticipated a lower salary this year than in the previous year. According to the data collected, over 94% of respondents reported being full-time employees, with others 2.4% working part-time and 2.0% retired. The unemployment rate among respondents stayed low in 2018, at less than 1.5%. The total was a tenth of a percent higher than the level from a similar survey in 2017, but still well below the overall unemployment rate for the U.S., which dropped to 3.7% for all workers in October 2018, according to BLS. The unemployment rate from a year before was 4.1%. ❑

Expanding career scope

The growth in demand for chemical engineers and those with related expertise has been partially driven by a profound expansion of the traditional domains for chemical engineering jobs. The field of chemical engineering has arguably always been diverse, but today's chemical engineers have a far wider range of possible employment opportunities than at any time in the past.

"The field of chemical engineering is dynamic, and continues to grow," says Shrikant Dhodapkar, research fellow at the Dow Chemical Co. (Midland, Mich.; www.dow.com). "It continues to gobble up new, adjacent and allied fields, such as biological processes, nanotechnology, pristine processing, safety-related issues, environmental management and more, so the umbrella gets bigger and bigger, providing new and interesting avenues for chemical engineers to explore."

The comments from Dhodapkar appear in a recently published book called "Careers in Chemical and Biomolecular Engineering," [*1*] which outlines areas where chemical engineers are employed and profiles working engineers in a far-flung range of professional roles. In another profile from the book, Irvin Osborne-Lee, head of the Department of Chemical Engineering at Prairie View A&M University (Prairie View, Tex.; www.pvamu.edu), remarks that "Chemical engineering is an endlessly flexible, adaptable and dynamic field of study that is forever launching entire new technologies."

Freeman Self, Bechtel (Houston; www.bechtel.com) design engineer and fellow, supports this perspective: "The demarcation between traditional fields is blurring, with so many chemical engineering advances that continue to be used by, and benefit, many different industry sectors."

Establishing future directions

The increasingly rapid evolution of the chemical engineering field and its connections to related fields is prompting thought leaders in chemical engineering community to take a fresh look at the directions into which the field appears to be moving in coming years. One example is current activities on the part of the U.S. National Academies of Sciences, Engineering and Medicine (NAS; Washington, D.C.; www.nationalacademies.org).

In 1988, NAS published a report called "Frontiers in Chemical Engineering: Research Needs and Opportunities" (Figure 2). The report was an effort to produce a roadmap for "turning promising research opportunities into reality, while guiding university educational efforts to embrace new frontiers."

Now, 30 years after the publication of that study, NAS is planning another report to "outline a vision for the chemical engineering discipline and

point the way for research, education and workforce development directions over the next 25 years." Tentatively titled "Chemical Engineering in the 21st Century: Challenges and Opportunities," the study will be organized and managed by the NAS Board on Chemical Sciences and Technology (BCST), and has a planning committee led by Joane Brennecke, professor of chemical engineering at the University of Texas at Austin (www.utexas.edu).

NAS

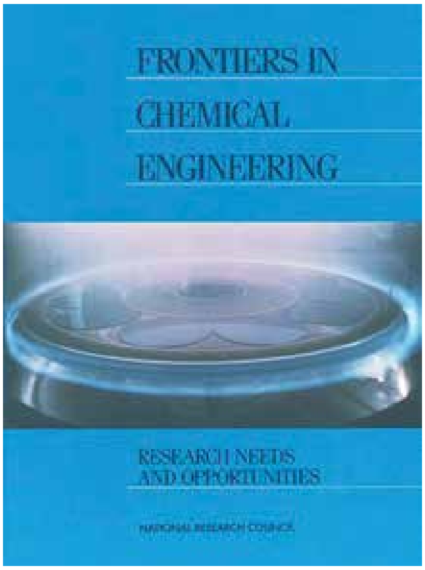

FIGURE 2. Plans are underway to update this 1988 National Academies report on chemical engineering

To support development of the study, the committee has raised $300,000 from the chemical engineering community so far, and has also secured additional funding from federal scientific funding agencies, including the National Science Foundation (Alexadria, Va.; www.nsf.gov) and the Department of Energy Office of Science (Washington, D.C.; www.energy.gov). The NAS study report is expected to be delivered in autumn of 2020.

The new report aspires to "articulate and transform the chemical engineering profession, guiding its vision of future research, innovation and education." It also will address other topics, such as the changing needs of industry in the 21st century, effective engagement with related fields, strengthening diversity, modernizing educational curricula and others, the NAS planning committee states.

Emphasizing the need for the chemical engineering discipline to continue to evolve in future decades to address the rapidly changing needs of society while taking advantage of new scientific capabilities, the NAS planning committee points to several specific areas that are affecting how research priorities, education and the practice of chemical engineering are viewed. These include advances in computing power and communications technologies that have changed how chemical engineers model and design, monitor, control and protect manufacturing processes and products. Computational power also has implications for predicting outcomes, managing data and publishing results. Related to the computing aspect is the the advent of data science and analytics, machine learning and artificial intelligence, all of which will have implications for chemical engineering research and process design, says the NAS planning committee.

Another concept likely to frame the forthcoming NAS

FIGURE 3. A new engineering-only university in the U.K. will focus on project-based problem solving and will not have separate departments

report is the "growing transdisciplinary nature of the field," the committee says. Embracing this multidisciplinary nature will have major impacts on education, training and workforce development in chemical enginering, the planning committee states. The study will also consider the growing focus on sustainability in process design and manufacturing, changing feedstocks and the advent of process intensification.

Evolving education approaches

Already, initiatives are underway to modify the approach to chemical engineering education, with an eye toward the future and with a focus on the transdisciplinary nature of chemical engineering roles.

For example, in the U.K., there has been an inauguration of a "from-scratch" engineering-only future university, the New Model in Technology and Engineering (NMiTE), designed to approach education differently than traditional programs, and create a project-based educational experience (Figure 3). The U.K. has a shortage of engineers, so the future university project is being set up partly to address this, but also has as its impetus, a number of other factors. Traditional engineering programs are good at producing graduates with a high level of academic knowledge, but who may not be as adept at applying knowledge to new problems, working in teams, communicating, and other requirements of today's modern workplace.

"When students are trained within a set of narrow fields, they tend to view engineering challenges through the lens of that specialty," explains Dave Allan, a professor at NMiTE. "What we are trying to do is to begin with the problems, and allow the challenges to guide the learning, rather than teaching the solutions and then trying to apply those to the problems."

"Currently, the rate of change in technologies is too fast to teach anyone all of the technical material that could be relevant," Allan continues, "so we are looking to provide a basis in fundamental engineering principles and then fill in the gaps in technical knowledge according to the problems we are facing."

The new university which is located in Hereford, U.K., is deliberately devoid of specific departments, recognizing that modern challenges are largely multidisciplinary. Subject to validation, NMiTE, which has been planned for 7 years, will welcome its first cohort of students in the fall of 2019. Students will attend lectures and laboratories for 8-hours per day, year-round, and will finish an accelerated Masters degree in three years. They will work onsite with various employers, tackling real-world projects that contribute toward their degree.

"You won't come here to study engineering; you'll come here to be an engineer," says NMiTE. "So our learner engineers will work collaboratively in small groups, on real-world engineering problems set by real-world organizations, mentored by real-world engineers."

NMiTE was inspired by a previous effort in the U.S. — namely Olin College of Engineering (Needham, Mass.; www.olin.edu). Olin was among the leaders in projects-based engineering education, a concept that has been increasingly taking hold in universities across the country.

Explaining Olin's approach, Rob Martello, associate dean of faculty and professor of the history of science and technology, says "The grand challenges facing our 21st century society do not obey disciplinary boundaries, and progress cannot depend on the simple application of a content set. Students need to learn how to learn, need to be comfortable with ambiguous problem framings, and must remain constructive in the face of repeated setbacks and unexpected challenges."

Continuing, Martello argues that engineering education needs to create a learning environment and culture that "prepares students to become interdisciplinary problem solvers by offering numerous authentic opportunities to learn and demonstrate teamwork, research proficiency, communication skill, the ability to learn on the spot, and strategies for approaching problems that lack a single right answer."

Each summer, Olin runs a week-long interactive workshop for university engineering educators on "Designing Student-Centered Learning Experiences." As it helps other universities, Olin continues to refine and innovate in its own educational approach. For example, Martello says Olin is creating a growing number of interdisciplinary project experiences that blend technical and nontechnical knowledge, skills and attitudes.

And looking forward, Martello says Olin's new focus over the next few years will be to add ethics and values throughout its technical curriculum, not as standalone philosophy courses, but as fundamental components of every engineer's practice. ■

Scott Jenkins

1. Edwards, V.H. and Shelley, S.A., "Careers in Chemical and Biomolecular Engineering," CRC Press, Taylor and Francis, Boca Raton, Fla., 2018.

Modern Simulation Tools: Expanding Applications

New user-friendly solutions help chemical processors tackle tasks beyond design and optimization

IN BRIEF

SOFTWARE ADVANCES

A WIDER BERTH OF APPLICATIONS

PLANT SAFETY

RELIABILITY

TRAINING

CORPORATE GOALS

Aveva

FIGURE 1. The SimCentral Simulation Platform from Aveva can improve the workflow, safety and design of a chemical process

Initially, steady-state simulation was used in the chemical process industries (CPI) to design a plant or a process. Advances in the technology, along with the need to produce more product in a more efficient and profitable manner, kick started the trend of using simulation tools to optimize new and existing processes. Today's dynamic modeling, digitalization, more powerful computers and swifter calculation capabilities have led to increasingly prolific use of software by engineers in all facets of the chemical facility. Simulation software is now readily available to help with specific tasks, such as improving safety, operator training, increasing reliability and achieving corporate goals, including sustainability, energy efficiency and, of course, profitability.

Software advances

While steadystate simulators have been around for nearly 50 years and are still the go-to tool for designing and optimizing new processes or plants, the introduction of dynamic simulation has led to a wider berth of applications. "While steady-state simulators are doing a good job, dynamic simulators are the way to go for improving existing processes or checking the operability of a new plant," says Marina Velazquez, senior product manager with Aveva Group plc (Cambridge, England; www.aveva.com). "Steady state is typically used early in the design to calculate sizing parameters and it assumes that the finished plant, equipment size and piping are exactly as they were designed. However, by startup, the location or size of the equipment and final piping may not be exactly as expected by the steady-state simulator. A dynamic simulator accommodates these differences and can be used to determine whether the control scheme is adequate, equipment will perform as expected, interlocks for safety are properly designed and more."

Meanwhile, digitalization is further expanding the use of simulation. The "digital twin" is an exact replica of the physical plant, not as designed, but as it actually exists. It also incorporates live process and operating information from the operating plant. "The digital twin provides an accurate representation that is always 'alive,'" says Rebecca Elgebrandt, portfolio marketing lead for Aveva's engineering business. "Since the digital twin incorporates differences between the design of the plant and the actual plant, it moves the simulation needs from steady state to dynamic and provides the current status of the true assets, allowing users to run a simulation with 'what if' scenarios in an accurate twin of the plant before taking any actions."

Roger-Marc Nicoud, CEO of Ypso-Facto (Nancy, France; www.ypsofacto.com) agrees that digitalization is an important step in simulation. "With a virtual/digital representation of a given process, one can easily experiment, test, train and explore operating conditions without the time and cost induced by real-life experimentation and without endangering real-life production."

In addition, digitalization allows easy sharing of information between multiple engineering disciplines. "Operating processes and

facilities requires the joint expertise of molecule specialists and simulation experts, of industry engineers and scientists and others, all with the single shared goal of inventing the best possible processes in an unbiased manner," says Nicoud. "And, today's simulation tools aim to bring all the necessary actors together and facilitate collaboration."

Velazquez agrees that information sharing is a growing necessity. "Integration is becoming more important so that all the process data can be shared among all the engineering disciplines," she says. "The final design, sometimes completed two or three years after the first simulation was done, can be checked easily by the dynamic simulation before starting up, reducing and avoiding costly last-minute updates at startup. Chemical processes can benefit from checking operating and control schemes prior to startup and from other simulation activities such as operator training, and digitalization allows better integration to make the necessary information sharing and collaboration easier for all the disciplines involved in these steps," she says (Figure 1).

Increased speed and improved user friendliness are also moving simulation into more applications. "While many simulation solutions are perceived as being very accurate, often the other perception is that they are time-consuming and take a lot of experience to use," says Ahmad Haidari, global industry director, process, energy and power, with Ansys (Canonsburg, Pa.; www.ansys.com). "However, newer versions don't require the same amount of experience and hands-on time as prior versions, which makes simulations more accessible and much more routine in the chemical processing industry."

For example, Ansys is focused on task-based workflow, which presents only the features and choices relevant to the task at hand and has best practices built in. "This provides the ability to use defaults and still get good answers, and also to customize and build workflows so that other engineers with less simulation experience can duplicate results. We are finding that this allows engineers to accomplish simulations two to three times faster than in the past with significantly less training," explains Haidari.

The company is also working to improve meshing. "One area that has been frustrating with fluid-dynamic-based solutions has been the meshing process, because in order to get a good mesh for use with simulations, a certain amount of hand-repetitive tasks were necessary to fine tune that mesh," he explains. "We are automating that process through a new technology to virtually eliminate the hands-on piece. Things that took two to three weeks to prepare are now getting done in hours. Engineers who are really experienced in chemical engineering, but don't have experience with fluid dynamics will be very successful using these tools," he says (Figure 2).

Another example is Chemstations (Houston; www.chemstations.com), which is launching a new version

Ansys

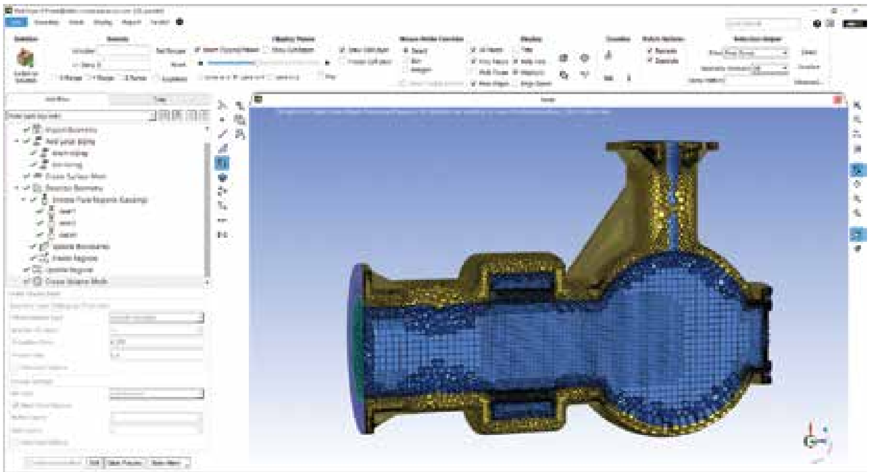

FIGURE 2. Ansys Fluent's Mosiac-enabled task-based workflow meshes complex geometries twice as fast with minimal user inputs

of its first-principles-based simulation software with improved calculation speeds that come via parallel processing that uses all available computing cores. "This means that instead of using just one core of the user's computer, we can spread the workload across as many cores as are available, which will speed the process considerably," explains Steve Brown, president of Chemstations. While the initial intent of the improved calculation time was to allow faster execution of large optimization projects, Brown says the increased speed also allows the software to be used for smaller projects. Wendy Young, marketing manager with Chemstations, agrees: "In the past, scaled-down versions of optimization, such as a sensitivity study, would take too long, but the calculation time has been reduced to such a degree that engineers are more likely to run simulations for smaller studies."

A wider berth of applications

While simulation tools used to be firmly rooted in design and optimization of plant and processes, digitalization, easier collaboration and user friendliness have opened the door for the use of simulation throughout the plant.

Plant safety. "The evolution of computational power and the capabilities of the software have given engineers a chance to solve some different, even possibly more complex, problems, with a higher degree of confidence," says Haidari with Ansys. "Safety is one of the areas where simulation is now being applied to determine why or when leaks, corrosion or other factors that deteriorate performance and directly impact safety of the process and personnel are happening."

For example, leaks may occur due to deteriorating seals or erosion of equipment, but because advanced tools allow users to model seals or examine corrosion in a given operation, the potential for failure can be determined. If there is a leak, simulation can be used to look at how gas may be dispersed within the plant using all sorts of possible scenarios, including wind and location of stacks. Safety valves can be better designed via simulation tools, and advanced software allows users to simulate what happens when an explosion occurs so they can better design equipment and plan for an emergency.

Paige Marie Morse, chemicals industry marketing director, with AspenTech (Bedford, Mass; www.aspentech.com), agrees that simulation tools can be helpful in the area of plant safety. For example, the company has acquired Blowdown software technology, which is used to identify locations in a system where temperatures can decline dramatically during depressurization. Blowdown has been incorporated into Aspen Hysys in order to provide an accurate determination of these low temperatures, which is a critical activity in the design and operation of process plants as it can improve safety of the plant (Figure 3).

Simulators can also be used to avoid unnecessarily purchasing safety systems. "A digital twin environment can be used for testing levels of protection, as well as for reducing and evaluating capital investments for safety stewardship," says Mart Berutti, vice president of process simulation with Emerson (St. Louis, Mo.; www.emerson.com). "The investment of capital in process safety is necessary and very important, but it's not one that increases the production of the plant. Simulation can help processors evaluate what levels of safety protection are required and eliminate the systems that aren't necessary."

Reliability. Today's simulators can also be used to enhance reliability of the plant and equipment, says An-

AspenTech

FIGURE 3. Simulation used throughout the entire plant asset lifecycle improves safety and other pillars of operational excellence

ProSim

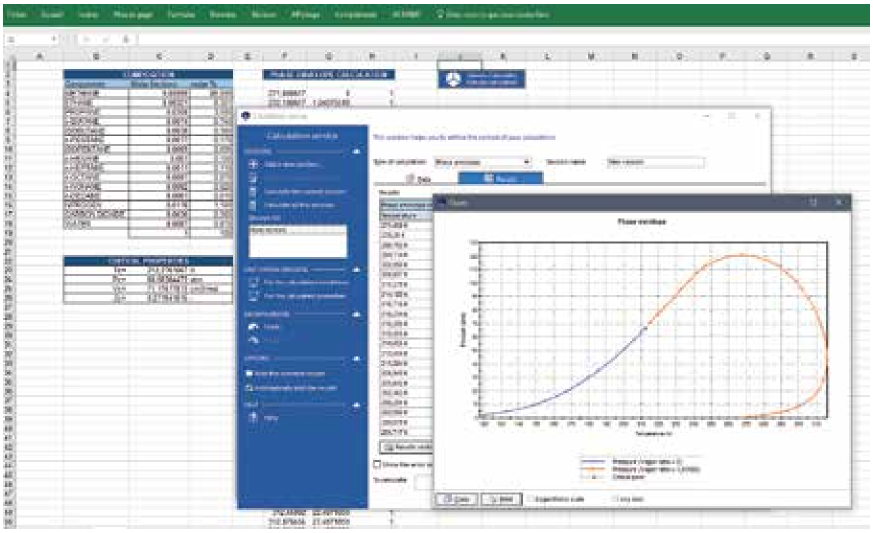

FIGURE 4. ProSim's Simulis Thermodynamics provides the thermodynamics knowledge needed for chemical process simulation. It is available as a Microsoft Excel add-in, a toolbox in MatLab or as a software component that can be plugged into any other application/software requiring reliable and accurate thermophysical properties. The figure shows a phase-envelope calculation diagram

sys's Haidari. "We call this 'fitness for service,' which means we look at things like fouling or degradation that may impact the performance of equipment. It is possible, through simulation, to look at a given design, either before it is built or during operation, and examine the range of operating parameters and variables it will be exposed to and understand the life of that asset," he says.

Further, he says it is possible to use simulators to look at issues that may be occurring, such as vibration, and use the model to perform a cause-and-effect analysis to understand why it may be vibrating and remedy the situation.

Training. Training is another area where simulators are making a major impact. "There's a lot of interest in the use of simulation for operator training," says AspenTech's Morse. "The advantage of using a digital representation of the plant is that it allows you to, offline, take operator trainees through different scenarios. Because it is a digital twin, it reflects what is going on at the unit so operators can learn how to handle various tasks without making an impact on the actual plant. It can also be used to train new operators before a newly constructed plant is up and running.

"Additionally," Morse continues, "Simulation can be used to create scenarios that involve process upsets, safety emergencies or environmental incidents and train operators to react so that events are properly managed and so operators have experienced the issues and don't panic in a real-life incident."

Emerson's Berutti agrees that simulator training is a vital application. "Statistical information shows that it takes six to seven years for a chemical plant operator to be able to make good risk-based decisions concerning operation of the plant, but most facilities are not in a position to spend this amount of time getting operators up to speed," he says. "A digital plant environment provides us with a time machine. It allows new operators to get comfortable with running the plant and controls for daily operations without actually practicing in the real plant. And, operators can have experiences — upsets and failures — that we would never want to see, but if they happen, the operators have had the opportunity to experience them over and over in the digital twin. This allows them to think clearly and not be intimidated by the gravity of a situation and have the competency to handle it. It makes them ready to operate the plant and

deal with emergencies in a shorter period of time."

Corporate goals. Modern simulation tools can also help processors achieve corporate goals, including energy efficiency, sustainability and profitability. "Simulation was created for the purpose of increasing efficiencies, so it makes sense that it is used for corporate goals such as sustainability and energy efficiency," says Stephane Dechelotte, CEO at ProSim (Labege, France; www.prosim.net). "Advances in software, such as better thermodynamic models and those specifically designed to assist with energy evaluations, allow better simulations of energy estimation and profitability calculations. Today's users require models that are predictive and that cover a wide range of mixtures, temperatures and pressure conditions, so thermodynamic models are a critical component to running simulations that achieve corporate goals, such as energy efficiency and the impact it has on yield, he says" (Figure 4).

Chemstations's Brown agrees that simulation is finding greater application in this area. "Companies will do an analysis to see where they can boost profitability and this is almost always tied to energy consumption. However, the same company may also consider energy efficiency a corporate social goal," he says. "We've seen them use simulation to perform a multi-objective optimization where they have the first objective as profit and the second as the societal or environmental impact. They can use the simulation to look at how they may want to operate the facility and examine the results and decide, on a corporate level, with input from various engineering disciplines, where to balance profitability with social or environmental impacts. They can find the overall optimum that works for their company."

These same types of simulations can be applied to almost any corporate goal, says Ansys's Haidari. "The process industry is becoming very interested in sustainability and as such ,is looking at things like resource scarcity, emissions reduction and pollution control, shifting to a low-carbon economy and other social aspects of processing," he says. "Today's easier-to-use and advanced simulations allow processors to perform studies around sustainability goals such as waste treatment, improving reactions to reduce the amount of heat created, taking wasted resources and putting them back into the process, reducing emissions, improving energy performance and reducing or recycling water or other resources used in the process."

What it comes down to is that today's simulators are capable of doing more than those of the past and they are able to do it dynamically and digitally, while sharing accurate and up-to-date information with everyone in the plant who might need it. "Safety issues, energy issues, control issues, reliability issues…all these issues can be solved if the engineers can communicate amongst themselves in the same language and that language is simulation," states Chemstations's Brown. ■

Joy LePree

Focus on Packaging and Transportation

Self-adhesive pipe labels improve workplace safety

ANSI/ASME A13.1 recommends the marking of all pipes to clearly communicate their contents, to improve facility maintenance and safety. This company offers a variety of premade pipe marking labels (photo), which are ready to go and easy to apply. More than 255 self-adhesive pipe labels are available, and these can be combined in thousands of variations, to clearly identify pipe contents. — *Graphic Products, Beaverton, Ore.*
www.graphicproducts.com

Round foil seals are peelable, allow for residue-free removal

To eliminate tampering or contamination throughout the entire supply chain, the outlet valves of intermediate bulk containers (IBCs) often include a seal foil that must be removed by cutting prior to initial product discharge. This solution can incur some problems of its own, as the product may come in contact with metal in the aluminum residues of the foil at the cut edges and the side facing the outlet valve. This new, easy-to-handle peelable seal foil (photo) protects the outlet valve of IBCs. It consists of several layers (mainly polyethylene terephthalate). In use, a flexible tab on the round seal foil is lifted, allowing the seal to be removed completely with no tools and no residue. The new seal foil is approved for use with food, says the company. — *Schütz GmbH & Co. KGaA, Selters, Germany*
www.schuetz.net

This device inverts pallet loads swiftly and safely

The PalletPal Rotator Inverter (photo) offers a fast, safe and easy way to invert a fully loaded pallet without the need for labor-intensive, time-consuming manual restacking. The most common use is for switching loads from in-house pallets to shipping pallets. Other uses include replacing broken pallets, replacing damaged boxes or bags, or turning over inventory, says the company. During operation, the load is placed into the unit with a forklift or stacker. The operator then engages the powered clamping mechanism to secure the load. At the touch of a button, an anti-friction turret bearing rotates the load a full 180 deg in about 15 seconds. The rotation can be stopped at any point during the process. The clamping mechanism features adjustable pressure to prevent the crushing of lighter loads. Models are available with a load capacity of 4,000 lb, and clamp openings accept pallet loads as large as 48x48x84 in. —*Southworth Products Corp., Portland, Maine*
www.southworthproducts.com

This compact machine combines labeling, cartoning

The Track Pack machine (photo) is an all-in-one solution for the tamper-evident aggregation, packing and serialization of pharmaceutical products. This compact machine (with a footprint of 3.5-x-2.3 m^2) comes with the company's case packer PS 300 and labeler BL A415. Track Pack is versatile, allowing users to mount tamper-evidend heads or to apply self-adhesive, tamper-proof seals on the closure corners of the carton or labeling heads. The conveyor assembly includes a patented timing device that sets the cartons apart correctly on the adjustable, toothed, slip-proof belts. The Track Pack system is able to serialize and group every kind of box and carton for both pharmaceutical and cosmetic industry products, at a production rate of 120 cartons and 4 cases per minute, according to the company. — *Marchesini Group, Pianoro, Italy*
www.marchesini.com

Graphic Products

Southworth Products

Schütz

Marchesini Group

Note: For more information, circle the 3-digit number on p. 158, or use the website designation.

Cortec.

EMP Closures

Additive gives papers and cardboard improved strength

The Cartastrength DST.03 liquid additive allows manufacturers of packaging (including corrugated fiberboard), and tissue papers, wipes and napkins, to manufacture products that have increased wet and dry strength (even those containing recycled fibers as a main raw material), compared to competing products, according to the company. The additive replaces starch, an improvement that can improve tissue attributes while also reducing chemical oxygen demand (COD) loadings in the manufacturing effluent. — *Archroma, Reinach, Switzerland*
www.archroma.com

This cartoner is both compact and ergonomically designed

The highly automated Promatic PCI 915 intermittent motion cartoner has a very small footprint (with a length of just 3.5 m). It is used mainly for the secondary packaging of blister packs, sealed strips and bottles. It can be configured either as a standalone machine or in line with a primary packaging unit. The machine has a maximum output of 160 cartons per minute. — *Romaco Group, Karlsruhe, Germany*
www.romaco.com

One-stop shopping for international transportation

This company specializes in managing the complex logistics that are associated with managing liquid goods, to ensure the sustainable handling of resources, the precise forecasting of requirements, and efficient international and intermodal route planning. Targeted products and consulting services are available related to track-and-trace capabilities, vendor-inventory management, geofencing, smart tank management and other forms of supply chain solutions. For example, the company's Smart Tank sensors report temperature deviations, while its track-and-trace capabilities provides information on journey time deviations. The company's Geofencing capabilities proactively tell customers the expected loading and unloading times, while the company's Electronic Data Interchange (EDI) supports smooth, fully automated logistics, delivery notes, certificates, invoicing and more. In-house expertise is available to help companies develop digital solutions related to intermodal supply chains. — *Hoyer Group, Hamburg, Germany*
www.Hoyer-Group.com

Advanced packaging safeguards machined parts

Protecting newly manufactured metal parts from rust and corrosion is a top priority for manufacturers and metalworkers who want their goods to arrive in excellent condition. Cortec VpCI papers, films and boxes are enhanced with vapor-phase corrosion-inhibiting technology (photo) to limit exposure to oxygen and moisture. Instead of applying greasy rust-prevention materials — a time-consuming and messy step — the producer of the part can simply wrap clean, dry and freshly machined parts in a sheet of VpCI paper or film, or place them in VpCI boxes. When the parts arrive at their destination, they are taken out of their packaging corrosion-free and ready to use. To guard against damage from oxygen and moisture exposure, the vapor-phase corrosion inhibitor molecules in the packaging evaporate and condense, forming an invisible, protective layer on the surface of the metal objects enclosed within the packaging. Once the machined part is removed from the package, the protective layer evaporates off the surface, with no extra step required. The used film and packaging can then be recycled. A broad array of standard and customizable paper and film variations are available, as needed. — *Cortec Corp., St. Paul, Minn.*
www.cortecvci.com

This broad array of caps and closures will fit your needs

This company has expanded the number of standard sizes and styles of caps and closures (photo) as part of its stock closures product line. These include closures with ribbed and smooth side walls, matte and smooth tops, continuous thread and snap lids and a tamper-evident snap lid. Both stock closures and custom packaging solutions are available for a wide range of markets, including food and beverage, personal care, chemical, pharmaceutical and nutra-

ceutical products. A variety of liner materials can be added to most of these stock caps and closures. — *EMP Closures, Div. of Erie Molded Plastics, Erie, Pa.*
www.emclosures.com

Universal suction cup has a tender touch and a strong grip
The FPC Series Suction Cup (photo) is a universal suction cup that can be used in a variety of applications, across various industry sectors — for handling fresh fruits and vegetables, for food-processing operations, cosmetics handling, laboratory applications and more. Designed to be ultra flexible, the edges of the suction cup will conform to the product, regardless of shape or material, enabling high production rates, says the company. The FPC Series product line benefits from three major innovations: The suction cups are available with round or elliptical shapes, their thin, flexible lips mold seamlessly to the packaging, regardless of the shape and internal cleats allow for optimized vacuum while preventing any crushing and strengthen the hold of the product being handled. Its fittings feature a lateral vacuum distributor that prevents any loss in efficiency when the product is held. Food-grade silicone and plastic inserts meet FDA food standards (FDA 21CFR 177.2600) and European standards (EC 1935/2004). — *Coval Vacuum Technology, Inc., Raleigh, N.C.*
www.coval.com

Coval Vacuum Technology

This powered transport device enables safe drum transport
The Liftomatic Ergo-PWPL-750 power transporter (photo) simplifies drum handling for operators. This self-contained, powered, drum-handling transport machine engages, lifts, lowers and moves steel, plastic and fiber drums. Its power drive moves in a forward and reverse direction, and provides power lift and lowering capabilities. Depending on the model, it provides varying weight capacities between 650 and 1,000 pounds. The Liftomatic Ergo-Matic

Liftomatic Material Handling

The Kurz Group

Herma US

Omron

line is equipped with a fully programmable set of controls for easy operator adjustment. The company's exclusive Parrot-Beak clamping mechanism allows the operator to safely and securely grip the drum lip throughout the pickup and release process. Additional features include regenerative braking, available in straddle leg or fully counterbalanced versions, as well as spark-resistant ratings. — *Liftomatic Material Handling, Buffalo Grove, Ill.*
www.liftomatic.com

These barcodes allow for hidden authenticity features

Barcodes are routinely printed in black, using thermal transfer printing (TTR), on machines, replacement and automotive parts, chemical and building materials, printed circuit boards and pharmaceutical packaging. Barcodes printed using this company's TTR Unique Verospec thermal transfer ribbons (photo) combine special customizable coatings to provide hidden, machine-readable authenticity features that help protect original items and reveal counterfeit products. By scanning these barcodes (with their unique fingerprints) with a special reader, the authenticity of the labeled product can be verified unequivocally, says the company. Different variants of TTR Unique Verospec can be used for different delivery units or product variants, allowing the authenticity of the goods to be checked at every station of the supply chain. — *The Kurz Group, Fürth, Germany*
www.kurz.de

This high-speed machine applies adhesive labels

The high-precision Herma 400 label applicator (photo) is available for both end users and original equipment manufacturers (OEMs). The compact module features a 400-W servo drive that achieves speeds in excess of 4,000 in./min, or up to 1,000 products per minute, with label registration accuracy of 0.008 in., says the company. The versatile Herma 400 can apply any type of adhesive label to virtually any type of product or package, and is used across a wide variety of industries, including pharmaceuticals, cosmetics, logistics, food and beverages, and the automative and chemical sectors. Depending on the machine type, the applicator can be installed in a horizontal, upright or suspended position. Thanks to the wide range of ancillary modules available, the Herma 400 can be integrated into any production line, or built into a labeling machine specifically developed to suit individual requirements. — *Herma US Inc., Fairfield, N.J.*
www.herma.us

Traceability products extend this automation portfolio

This company offers a broad portfolio of integrated automation solutions, including robotics, sensing, motion, logic, safety and more. The HAWK MV-4000 smart camera, MicroHAWK ID-45 reader and HS-360X handheld barcode reader (photo), which enable improved traceability and inspection during electronics and automotive manufacturing, food-and-beverage packaging and other industries. — *Omron, Hoffman Estates, Ill.*
www.omron.com

Reduce the risk of landing gear collapse at loading docks

Heavy loads in front of the landing gear, uneven loads and faulty landing gear can all cause a trailer nose to drop. The Rite-Hite TS-5000 uses a wide top plate (12x66 in.), twin vertical supports and dual base plates to provide stabilizing support, which can prevent accidents during the loading or unloading of trailers at loading docks. The static load capacity of the Trailer Stabilizer is 70 tons (140,000 lb) is more than three times the combined maximum weight allowed for a forklift and load today, according to the manufacturer. Three 13-in. tires and ergonomic positioning handles allow the Trailer Stabilizer to be moved into position easily. An optional communication flag alerts worker and truck drivers that the unit is properly positioned. This versatile unit extends up to 56 in. and retracts down to 40 in. meaning it can service nearly all trailer configurations on the road. — *RiteHite, Milwaukee, Wis.*
www.ritehite.com ■

Suzanne Shelley

Patented technology for precise position detection

The new PMI F90 inductive positioning system (photo) works with a patented multi-coil system. The absolute position of the actuator is precisely detected from the measuring signals of a single coil. In addition to sending the analog position signal, switch points can also be defined. The sensor can detect two actuators, as well as the distance between them, meaning that dynamic positioning tasks can be completed with the smallest amount of measuring technology, says the manufacturer. Certified versions of the PMI product family allow the system to be used in ATEX Zone 2/22 (3G nA, 3D tc) hazardous locations. The compact design allows these sensors to be installed in even the tightest of spaces, while the rugged metal housing protects them from external influences. IP67 protection and a temperature rating of –25 to 85°C ensure reliable positioning in outdoor environments. — *Pepperl+Fuchs GmbH, Mannheim, Germany*
www.pepperl-fuchs.com

This data manager has extensive communications capabilities

The Memograph M RSG45 advanced data manager DIN rail version (photo) is an intelligent remote device with extensive communication capabilities for use as an edge device for getting data to cloud-based servers, as well as general industrial internet of things (IIoT) applications. It is able to acquire data from up to 20 HART or universal analog input channels and 14 digital inputs, has two analog outputs and up to 12 relay outputs, and makes its data available to IIoT systems and all major automation system architectures via multiple communication interfaces and protocols. The Memograph M mounts on a standard DIN rail and has IP20 protection. All connections on the front of the device are designed as pluggable screw or spring terminal blocks, with reverse polarity protection in either case, making connections easier. The spring terminals are unlocked with a slotted screwdriver. — *Endress+Hauser, Reinach, Switzerland*
www.endress.com

Achieve faster temperature calibration

The Jofra CTC-1205 compact temperature calibrator (photo) covers a temperature range of 100 to 1,205°C (212 to 2,201°F), with accuracy of ±0.2°C (±0.36°F), and stability to ±0.1°C (±0.18°F) for the total temperature range, along with improved calibration times when compared to its predecessor, the CTC-1200, says the manufacturer. The CTC-1205 features an intuitive interface, and popular functions, such as automatic switch test and auto stepping, are available with special one-key buttons. CTC Series calibrators are available in different models: with reference sensor; without reference sensor but ready for external input; and without external input. All CTC models come with the proprietary JofraCal calibration software as a standard. — *Ametek Sensor, Test & Calibration (STC), Berwyn, Pa.*
www.ametekcalibration.com

New scales connect easily to enterprise networks

This company has designed a new version of its E-Scale series of IIoT-connected bench scales (photo). With a direct industrial network connection via EtherNet/IP, Profibus-DP or Modbus protocols, the IIoT-ready scale base includes an integrated weight processor. E-Scales are suitable for pharmaceutical manufacturing, laboratory dry-goods processing and industrial installations. All E-Scales come standard in 12- and 24-in. sizes, and range in capacity from 33 to 1,300 lb (15 kg to 600 kg). Bench-scale covers are stainless steel for superior durability. Bases have no bearings, spirit levels or moving parts that could be easily damaged or worn out. — *Hardy Process Solutions, San Diego, Calif.*
www.hardysolutions.com

Smart lockout-tagout adds another layer of security

This company now offers Virtual Lockout-Tagout (vLOTO) capabilities with its Connect Power User Plans. vLOTO allows companies to control remote access to equipment, ensuring the safety and security of workers and equipment during critical operations.

Pepperl+Fuchs

Endress+Hauser

Ametek STC

Hardy Process Solutions

NewTek Sensor Solutions

Hemco

Badger Meter

If a worker needs to connect remotely to conduct maintenance, vLOTO can help protect the module from inadvertent harm by someone else on the same user team. This capability also offers more control over equipment to end users, who can grant access for a specific duration to machine builders or system integrators. Up to three authorized personnel can grant access, but if one person declines, the approval will be overridden. An audit trail lets an IT department know who granted permission. This technology is a first for remote connectivity applications, according to the company. — *ProSoft Technology, Inc., Bakersfield, Calif.*
www.prosoft-technology.com

Non-contacting RVDT sensors are shock and vibration resistant

The RV Series of rotary variable differential transformer (RVDT) position sensors (photo) offer highly accurate angular displacement measurement of rotating elements, such as quarter-turn ball and butterfly valves, actuators, throttlers and tensioners. With a shaft that rotates a full 360 deg with no stops and virtually no friction, these rotary position sensors measure shaft-angle position over a nominal range of ±30 deg. The sensors' non-contacting design enables a long operational life by eliminating components that wear or degrade over time. The devices are shock and vibration tolerant, even when operating in hostile conditions. Units operate over a temperature range of –65 to 220°F and exhibit a linearity error of less than 0.5% of full range. — *NewTek Sensor Solutions, Pennsauken, N.J.*
www.newteksensors.com

Safely store acids with these dedicated cabinets

This company's acid storage cabinets (photo) are specifically designed for the storage of corrosive chemicals and are available in 12-, 18-, 24-, 30-, 36-, 42-, and 48-in. widths, with a standard height of 35 in. and a standard depth of 22 in. The molded one-piece fiberglass liner inserts directly into the cabinet and is sealed on all edges for ease of cleaning. The interior features a containment lip on the front bottom edge to hold spills. The front access doors have air inlet vents and the edges are sealed. No metal is exposed to corrosive vapors. For smaller container storage, a removable shelf is included. — *Hemco Corp., Independence, Mo.*
www.hemcocorp.com

Smart actuation for control valves in extreme environments

SEVA electric valve actuators (photo) feature a microprocessor-controlled linear stepper motor to provide accuracy and repeatability. Built to withstand extreme conditions, two SEVA models are available, the SEVA-100 and SEVA-200, which provide torque for this company's control valves in sizes from ¼ to 2 in. The actuators have options for EtherNet/IP and ModBus TCP IP/RTU protocols and are certified by the Open DeviceNet Vendors Association. They also feature four positions when there is a loss of signal: fully closed, fully open, hold position or set value. Both the full-closed and full-open positions are defined during setup, and in the event of loss of power, there are five available positions: continue operation, fully closed, fully open, hold position or set value, plus a manual override capability. — *Badger Meter, Inc., Milwaukee, Wis.*
www.badgermeter.com

Readily integrate ERP systems with this asset performance manager

AllAssets is a new software-as-a-service (SAAS) platform for asset performance management that enables optimization of inspection and maintenance activities. Chief among the features offered by AllAssets is robust integration with enterprise resource planning (ERP) systems from a variety of providers, such as SAP and IBM Maximo. According to the company, AllAssets expedites model building, allowing users to construct a custom model in days rather than months, using code-free techniques. Once built, the custom models can rapidly provide new performance and risk insights to inform teams across an entire enterprise. The efficient data link with ERP systems further drives operational efficiencies, through greater clarity and certainty in maintenance and planning schedules. — *Lloyd's Register, London, U.K.*
www.lr.org/en/allassets/

Quickly contain leaking flanges and valves

The Xtreme Shell (photo) provides fast containment of a leaking flange, valve or any other connection point, virtually eliminating the costs of emergency shutdowns and the need for emergency repairs related to pipe flange and valve leaks, says the manufacturer. The Xtreme Shell can be installed with optional remote monitoring for a potential leak point or to divert an existing leak within minutes while on site or in remote locations. The Xtreme Shell is manufactured to ANSI pipe and flange standards to fit precisely over the leaking flange or valve. The diversion line, once secured, allows the containment vessel to be placed nearby. It can be used in a variety of leak-detection situations, including in utilities and energy distribution, electrical equipment, bottling and canning facilities and pharmaceuticals. — *Andax Industries LLC, Saint Marys, Kan.*

www.andax.com

These drives now feature an extended power range

This company has expanded the power ranges and capabilities of the TotalForce technology for its Allen-Bradley PowerFlex 755T AC drives (photo). The drives now offer an expanded power range, from 10 to 6,000 h.p. (7.5 to 4,500 kW). The expansion brings harmonic mitigation, regeneration and common bus-system configurations to a wider range of high-demand applications. Enhancements to the patented TotalForce technology include more powerful adaptive-control capabilities, which allow the drives to monitor machine characteristics that can change over time, and automatically compensate for the changes that occur. An adaptive tuning feature uses up to four automatic tracking notch filters to block resonance and vibration that can impact quality, waste energy and prematurely wear out a machine. In addition, predictive maintenance features provide realtime information about the health of the drive. By

Andax Industries

Rockwell Automation

Krohne

Lee Products

Liftomatic Material Handling

Morehouse Instrument

monitoring operational characteristics, such as temperature, voltage and current, the drive is able to calculate the remaining life of critical components and notify users. — *Rockwell Automation Inc., Milwaukee, Wis.*
www.rockwellautomation.com

An all-in-one water meter for remote locations

Waterflux 3070 (photo) is said to be the first water meter with integrated pressure and temperature sensors. The meter features simplified installation, integrated diagnostics, a long battery lifetime, remote communication options and low overall maintenance requirements. The updated Waterflux 3070 now offers a mains power option with battery backup and a Modbus RTU communication option for transmission of readings, meter status and alarms. The polycarbonate converter housing with protection class IP68 rating is now standard for both compact and remote versions. The meter features IP68 waterproof plug-and-play connectors that do not require wiring on site, and a small installation footprint to fit into electrical cabinets. The meter can be used for pressure monitoring and maintaining water balance, as well as leak detection when comparison of pressure and flow values is used as the leak-detection method. — *Krohne, Inc., Peabody, Mass.*
www.us.krohne.com

Miniature solenoid valves for critical fluid control

The LFV Series 8000 two-way inert solenoid valve (photo) is a miniature device whose small size ensures a more compact instrument footprint and means less fluid is needed, enabling closer valve spacing. These two-way, chemically inert, isolation-style valves provide an on/off function in a critical fluidic circuit, ensuring zero dead volume and extremely low internal volume. They incorporate a diaphragm seal that isolates the fluid from the inner components to provide a consistently reliable switching performance. They are also rated for bi-directional flow and feature a contoured path design, which allows for complete flushing capability. The valves are available with push-on ports for soft tubing or two-manifold mount styles, which now utilize O-rings instead of gaskets made from the same material as the diaphragm. — *Lee Products Ltd., Gerrards Cross, U.K.*
www.leeproducts.co.uk

Safely lift steel, fiber and plastic drums

The HCB hoist attachment (photo) is designed to handle all 55-gal drums, enabling safe lifting of steel, fiber and plastic drums weighing up to 2,000 lb. A padded belt cradle protects the drum sidewall during transport. The HCB is available in one- or two-drum configurations, including stainless-steel units for food-grade and pharmaceutical applications. Using this company's exclusive Parrot-Beak drum-handling attachment, the model HBC-BC attaches to any overhead hoist, crane or boom and engages drums automatically. An exclusive mechanical clamping system engages the top lip of the container, ensuring a safe and reliable container pickup, says the manufacturer. — *Liftomatic Material Handling, Inc., Buffalo Grove, Ill.*
www.liftomatic.com

Effective field calibration for force-measuring equipment

This company has introduced two new portable calibration machines (photo) — the PCM, with a 2,000-lb_f capacity, and the BCM, with a 10,000-lb_f capacity. The PCM is capable of calibrating various types of load cells, hand-held force gages, and other force-measuring devices with capacities from 25 through 2,000 lb_f while providing stable control to within 0.01 lb_f. The PCM eliminates the need for the technician to carry or stack weights, which protects employees, as weights are often heavy and can lead to injuries. The benchtop BCM model allows for calibration of force-measuring equipment with capacities of 100 through 10,000 lb_f. Both the PCM and BCM are designed with field calibration requirements in mind, and with the goal of providing all necessary force calibration tools in a portable package. — *Morehouse Instrument Co., York, Pa.*
www.mhforce.com ■

Mary Page Bailey

Distillation: Comparing Experiments and Simulations

Department Editor: Scott Jenkins

Computer-generated simulations of distillation processes are often validated experimentally. This reference discusses three concepts that influence comparisons between experimental results and simulation predictions: vapor-liquid equilibrium (VLE) of the components; relative liquid-to-vapor flowrates (L/V ratios in the column); and vapor-liquid contactor (tray) efficiency. Understanding these concepts can help explain discrepancies between experimental data and simulation results.

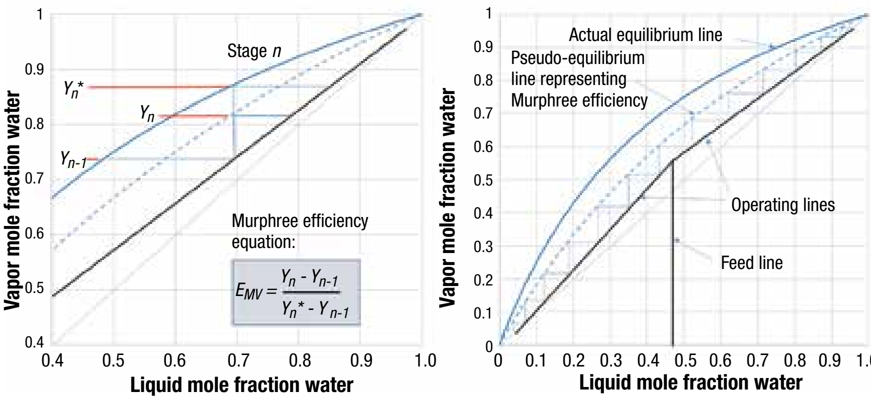

FIGURE 1. Murphree efficiency represents how close the actual vapor composition comes to reaching equilibrium with the liquid on an actual distillation tray. Non-attainment of equilibrium is shown as a pseudo-equilibrium line on a McCabe-Thiele diagram

Vapor-liquid equilibrium

The relative volatility of an ideal binary chemical system is equal to the ratio of the two pure-component vapor pressures. If the components' interactions are close to ideal and the components have sufficient relative volatility (>2), then small errors in VLE predictions may not significantly affect the separation. However, if the relative volatility is small (<1.5), deviations between predicted and actual VLE will lead to large differences between the actual and predicted number of stages required to accomplish the separation.

Non-ideal systems often have a pinch at the upper or lower end of the binary VLE curve (vapor and liquid compositions of both components are nearly equal). The pinch is usually at the upper (right-hand) end of the VLE curve. Here, the actual vapor pressure of the heavy-boiling component is nearly equal to that of the light-boiling component, due to the increased liquid-phase activity coefficient of the heavy-boiling component at infinite dilution. With sufficient non-ideality, the activity coefficient of the heavy-boiling component will become even greater, causing the heavy-boiling component's actual vapor pressure to exceed that of the light-boiling component at infinite dilution of the heavy-boiling component. This is the case for minimum-boiling azeotropes, and at the azeotrope composition, the actual mixture vapor pressures (pure-component vapor pressure × activity coefficient at the component's liquid concentration) of the two components will be equal. The closer the composition is to a pinch zone or azeotrope, the greater the effect of errors in the VLE prediction.

Liquid/vapor ratios

The relative vapor-to-liquid flowrates within the column are not only determined by the feedrate, reflux ratio, boilup ratio, and distillate-to-bottoms ratio, but also by heat effects. Excessive heat loss from a high-temperature column with many stages can significantly increase the internal reflux. This heat loss reduces both the liquid and vapor flowrates as one progresses up the column. The L/V ratio will be the lowest at the top of the column, where it can be experimentally determined from the reflux and distillate flowrates.

However, the L/V ratio will progressively increase as one moves down the column, due to condensation of the vapor. This effect can be thought of as an increase in the effective reflux ratio going down the column. This increase in L/V ratios due to heat loss will cause the column to have a better separation than predicted by a computer simulation, but at the expense of higher energy costs and lower capacity than expected. Without understanding that the actual L/V ratios are different than expected, the VLE curve would appear to be more open (higher relative volatility or less pinched) than is really the case.

Efficiencies

Process simulators generally use theoretical stages to represent trays in a distillation column, but in real columns, the vapor leaving a tray is seldom in equilibrium with the liquid from that tray. The difference between the actual and equilibrium vapor compositions can be expressed as a Murphree vapor efficiency. Values tend to range from 50–75% for lab- and pilot-scale columns, but can lie outside this range. The Murphree vapor efficiency is an indication of how closely the vapor composition in an actual distillation tray approaches equilibrium with the liquid leaving that tray (Figure 1).

At 100% efficiency, the number of actual trays required for a separation would equal the number of theoretical trays. At efficiencies less than 100%, the required number of actual trays will be greater than this theoretical number. Therefore, if the actual tray efficiencies are lower than predicted, more actual trays will be required to accomplish a desired separation than would be anticipated based on the required number of theoretical trays and the predicted efficiency. Without properly accounting for the reduced efficiency, the separation will appear to be more difficult than predicted.

The efficiency of packed columns is routinely expressed as HETP (height equivalent to a theoretical plate). If the actual HETP is greater than predicted, the column will contain less theoretical stages than predicted, producing similar results to a column with trays that have lower efficiencies. ■

Editor's note: This column was adapted from Graham, G., Pednekar, P. and Bunning, D., Experimental Validation of Column Simulations, *Chem. Eng.*, February 2018, pp. 30–37.

Polychloroprene Production

By Intratec Solutions

The need to find a substitute for natural rubber during World War II boosted the development of polychloroprene (chloroprene rubber), the first synthetic rubber produced industrially. Today, it is one of the most important special rubbers, alongside butyl rubber, nitrile rubber (NBR) and ethylene propylene diene rubber (EPDM).

The process

The following describes a process for polychloroprene production from butadiene and chlorine. Figure 1 presents a simplified flow diagram.

Chlorination. In the first step, butadiene, chlorine, recycled butadiene and hydrochloric acid are mixed and fed to the chlorination reactor, where butadiene is chlorinated in the vapor phase. A large excess of butadiene is used to prevent the formation of super-chlorinated species during this reaction. The two main products of the chlorination are 1,4-dichloro-2-butene and 3,4-dichloro-1-butene.

Isomerization. An isomerization step is used to convert 1,4-dichloro-2-butene into 3,4-dichloro-1-butene (the precursor to chloroprene). The isomerization is conducted in the reboiler of a distillation column. In this way, 3,4-dichloro-1-butene is continuously removed from the liquid reaction medium by evaporation. The 3,4-dichloro-1-butene is recovered from the top stream of the column, while the column's bottom product is recycled to the process.

Dehydrochlorination and purification. Caustic soda is diluted in process water, mixed with the 3,4-dichloro-1-butene stream from the isomerization step and fed to a series of continuously stirred vessels. The gaseous effluent is cooled, condensed and then settled for separating the organic and aqueous phases. The aqueous phase is discarded, while the organic phase is stripped against steam. This column is designed to recover a gaseous chloroprene-rich stream from the top, while the unconverted 3,4-dichloro-1-butene is recovered in the column's bottom.

The bottom product is then allowed to settle, in order to separate the organic and aqueous phases. Then the aqueous phase is discarded, while the organic phase is dried and directed to a falling-film evaporator. The evaporator is used to remove heavy-end byproducts.

The gaseous stream from the evaporator is mixed with the top stream from the stripping column, and this mixture is distilled for the recovery of 3,4-dichloro-1-butene (bottom) and chloroprene (top). Both column products are allowed to settle, and the resulting aqueous phases are discarded, while the organic phase is dried in molecular sieves. The dried column-bottom stream is recycled, while the dried crude-chloroprene stream is purified in a final distillation step and routed to the polymerization stage.

Polymerization. The polymerization is carried out in continuously stirred, jacketed tank reactors connected in series, and cooled by a brine solution. Chloroprene is first mixed with emulsifier, demineralized water and initiators (hydroperoxides/ferrous sulfates). The polymer molecular weight is controlled by means of a chain-transfer agent (tertiary dodecyl mercaptan). The reaction is terminated with the addition of shortstop agents (for example, sodium polysulfide).

Recovery and finishing. The latex produced is steam-stripped for the removal of residual chloroprene, which is recycled. The hot latex is mixed with antioxidants and fed to a freeze roll to be coagulated into a polymer sheet, which is fed to a wash belt for removing polymerization-reaction medium. The washed polychloroprene film is dried in squeeze rolls and continuous-belt dryers. After drying, the film is formed into a rope and cut into polychloroprene chips, which are packed in bags.

Economic performance

The total operating cost (including raw materials, utilities, fixed costs and depreciation costs) estimated to produce polychloroprene was about $2,400 per ton of polychloroprene in the fourth quarter of 2014. The analysis is based on a plant constructed in the U.S. with the capacity to produce 50,000 metric tons per year of polychloroprene.

This column is based on the report "Polychloroprene Production – Cost Analysis," published by Intratec. It can be found at the following URL: www.intratec.us/analysis/polychloroprene-production-cost. ■

Edited by Scott Jenkins

Editor's note: The content for this column is supplied by Intratec Solutions LLC (Houston; www.intratec.us) and edited by *Chemical Engineering*. The analyses and models presented are prepared on the basis of publicly available and non-confidential information. The content represents the opinions of Intratec only. More information about the methodology for preparing analysis can be found, along with terms of use, at www.intratec.us/che.

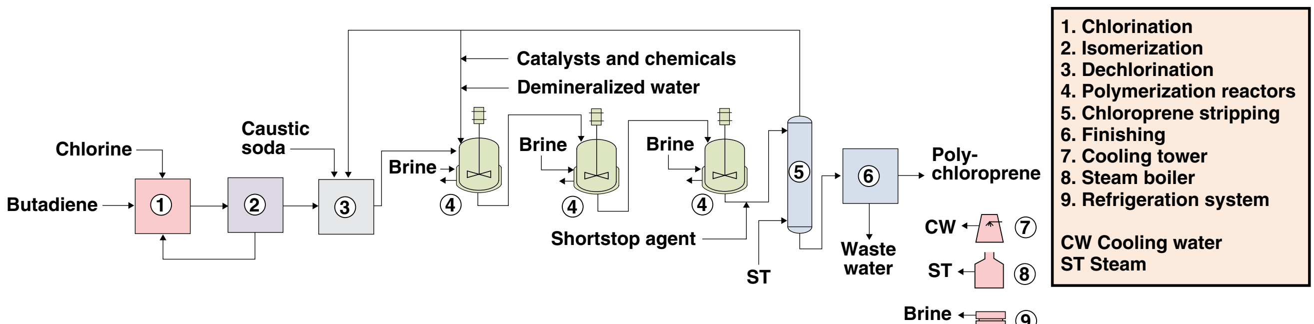

FIGURE 1. The diagram shows a process for the production of polychloroprene

Recent Air Regulations: Impact on Turnaround Vapor Deinventory Strategies

With the onset of new environmental regulations, turnaround teams must look to temporary vapor-control strategies to ensure compliance during non-routine operations

Paul Anderson and Chris Longo
GEM Mobile Treatment Services

IN BRIEF

TURNAROUND UNIT DEINVENTORY

TEMPORARY VAPOR-CONTROL PROCESSES

CHEMICAL CLEANING

PLANNING, DESIGN AND COMPLIANCE

FIGURE 1. Turnarounds are a challenging — but critical — part of any process unit's lifecycle, because they provide a window of opportunity to perform maintenance and other important tasks

Turnarounds are one of the most anticipated and time-intensive events in a plant's cycle, and are an essential part of continuous operations in the petroleum refining and petrochemical industries. A turnaround is a scheduled event wherein an entire process unit in a refinery or manufacturing site is taken offline for an extended period of time to perform maintenance, modifications, inspections, catalyst regeneration or changeouts, as well as any related projects (Figure 1). Turnarounds provide an important window of opportunity for essential maintenance tasks and allow for safe and efficient servicing or replacement of process equipment. If done correctly, turnarounds can potentially lead to huge gains in the facility's productivity and output. However, turnarounds are also extremely costly events in terms of direct costs for labor, tools, heavy equipment and materials used to execute these projects. If the budget balloons or the timeline unexpectedly expands, it can have disastrous effects on a company's bottom line.

Petroleum refinery turnarounds are becoming more difficult and increasingly expensive. New environmental regulations present potential challenges in turnaround performance by adding complexity, extending completion times and incurring additional costs. While facilities may be fully in compliance with these regulations during normal operations, it may be difficult to meet these rigorous standards during non-routine activities, including turnarounds and the associated unit shutdown and startup. Operators and contractors are constantly challenged with how to complete turnaround tasks quickly, safely and more efficiently. Temporary vapor-control systems can provide solutions to meet some of these regulatory challenges during non-routine events like turnarounds.

Turnaround unit deinventory

One important part of the turnaround process is the unit deinventory phase. Unit deinventory begins when feed is cut to the unit. Liquids and vapors are removed from the unit using a variety of transfer methods, including liquid pumping, pressuring off, inert-gas purging, steaming and chemical circulation or injection.

After deinventory is complete, the unit either undergoes chemical cleaning or purging to bring the unit's vapor concentration to the minimum level dictated by safety and environmental requirements. Once these activities are complete, the unit is safe to open to atmosphere and equipment, components and catalysts can be removed for further cleaning, inspection, repair and replacement as needed.

Numerous facility turnarounds are being impacted by environmental restrictions

FIGURE 2. New emissions regulations are causing operators to seek alternatives to flaring during turnarounds

FIGURE 3. Portable vapor combustion systems can provide an effective solution for environmental compliance during turnarounds

driven by the evolution of new federal standards from the U.S. Environmental Protection Agency (EPA; Washington D.C.; www.epa.gov) under the umbrella of Maintenance Startup and Shutdown (MSS) regulations and Refinery Sector Rules. These changes create the potential for bottlenecks and potential delays during the turnaround deinventory process.

In the past, refineries were granted much greater flexibility to vent emissions during turnarounds. A common approach for many states was to allow turnaround vapor deinventory activities to vent emissions to the atmosphere or flares. Venting could occur during depressurizing a unit, steaming or purging process equipment or chemical cleaning using steam or chemicals. The recent implementation of Refinery Sector Rules has made turnaround flaring an increasingly uphill battle.

Changes to EPA regulations, such as New Source Performance Standards 40 CFR 60 Subparts J/JA and Refinery Sector Rules related to the National Emission Standards for Hazardous Air Pollutants (NESHAP MACT CC and MACT UU), have imposed emissions limits and necessitated monitoring and reporting tasks that make flaring a less desirable option (Figure 2). Several examples of the impact of Refinery Sector Rules on refinery units are described in Table 1. In response, operators of facilities have increasingly looked to recapture vapors during maintenance periods through the use of flare-gas recovery units (FGRUs).

In FGRUs, liquids and gases are recovered the majority of the time. After recovery, they are cleaned and utilized as fuel gas in facility heaters and various other facility process units. Under normal operating conditions, essentially all gases that are produced are routed to the refinery fuel-gas system, allowing them to be used for combustion in refinery heaters and boilers. Typical refinery fuel-gas systems are configured so that the fuel-gas header pressure is maintained by adding excess natural gas to meet the net fuel requirement. This provides a simple way to keep the system in balance, so long as fuel gas needs exceed the volume of gaseous products produced. Flaring often occurs during unit startups and shutdowns or when pieces of equipment associated with a unit are taken out of service.

For safety and environmental reasons, equipment maintenance results in the need to remove source hydrocarbons from process equipment and associated piping before opening. Typical decommissioning procedures include multiple steps of depressuring, nitrogen, gas, or steam purging or chemical injection. During these steps, the quality of the fuel gas is degraded and at times cannot be recovered.

FGRUs are also limited due to their inability to accept or process certain vapor streams in a timely fashion. For example, nitrogen,

TABLE 1. SELECTED REFINERY SECTOR RULES' IMPACT ON PROCESS UNITS

Process unit	Refinery Sector Rule impact
Delayed coker (MACT CC)	Atmospheric venting requirement drops from 5 to 2 psig
Catalytic reformer (MACT UUU)	5 psig exemption removed. Active purging vents must now be routed to an emissions-control system
Sulfur recovery (MACT UUU)	For affected sulfur recovery units (SRUs), purge gas during startup and shutdown must now be sent to flare or incinerator
Fluid catalytic cracking unit (MACT UUU)	Must comply with Hazardous Air Pollutant (HAP) emissions previously exempt during periods of startup and shutdown
Distributed equipment (Pressure release devices) (MACT CC)	During startup and shutdown, prevent release of vapors until process fluids are removed and lower explosive limit (LEL) is brought below 10%

steam and hydrogen sulfide (H_2S) all present unique obstacles to the FGRU that can slow down or overwhelm its capabilities. A summary of these impacts on FGRUs and flares is given in Table 2.

As a result, refineries have begun identifying and addressing turnaround maintenance activities that may lead to problematic process streams being sent to the FGRU. Addressing these activities through the use of alternative vapor-control devices has allowed many facilities to recover lost time and return the team to its "pre-regulatory" turnaround schedules.

The curtailing of flare emissions by the EPA will have a broad range of practical implications on industry, but of particular concern will be the use of vapor-control equipment (FGRU and flares) during these periods of startup and shutdown. Some restrictions placed on flares, such as requiring minimum operating temperatures, specific component concentration or mass limitations and removal efficiencies, will often be difficult or impossible to achieve during these interim periods. Avoiding penalties during these spans may require facilities to utilize temporary vapor-control equipment designed specifically for periods of startup and shutdown.

FIGURE 4. Portable liquid H_2S scrubbers can be employed during turnarounds to remove toxic acid gases that pose environmental issues

Effective vapor-control strategies employed during shutdowns include flareless shutdown capability, hydrocarbon pre-treatment or eliminating the flare systems as primary destruction sources. Additional benefits include continuous environmental compliance involving monitoring, data recording and final compliance reporting documentation.

These vapor-control strategies are being successfully integrated into turnaround planning and serve as best practices for facilities recently challenged with meeting new environmental regulations associated with turnaround activities.

TABLE 2. IMPACTS TO FLARE-GAS RECOVERY UNITS AND FLARES			
Issue	**Impact**	**Solution**	**Benefits**
High gas volumes	Deinventory delays, compressor issues	Thermal vapor combustion	Improved fuel gas quality and reduced flare load
Nitrogen concentrations	Negative heating impact, compliance with NSPS J/JA (Continuous emissions monitoring systems; CEMS)	Thermal vapor combustion	Improved fuel gas quality and reduced flare load
H_2S concentrations	SO_2 compliance deviations, possible CEMS violation	Caustic scrubbing prior to thermal combustion	Environmental regulatory compliance
Steam volume and temperature	Compressor issues, limited reliability and performance	Heat exchanger and condensate-collection system	Improved reliability and predictable decontamination schedule

Temporary vapor-control processes

Newly emerging regulatory requirements brought about a need for a comprehensive approach to develop environmental vapor-control strategies. Processes for vapor and liquids removal and chemical cleaning are being integrated into the operational shutdown procedures to mitigate safety risks, eliminate environmental bottlenecks, shorten the shutdown sequence and increase schedule reliability, all while meeting environmental regulatory requirements.

Facilities must strive for vapor-control processes that mitigate problematic process variables and compounds that exist during the shutdown and cleaning processes prior to introduction into a facility's FGRU or flare system.

Temporary unit deinventory vapor-control processes include: thermal vapor destruction, liquid scrubbing, carbon adsorption, heat exchanger cooling and condensing, condensate removal, as well as pressure and temperature control. These temporary vapor-control processes are described in the following sections.

Thermal vapor combustion. This method involves processing hydrocarbon vapors or volatile organic compounds (VOCs) using an enclosed vapor combustion unit (VCU), which produces exhaust gases that are primarily carbon dioxide and water (Figure 3). The VCU is equipped with various automated safety devices, flow and combustion temperature transmitters and monitoring systems designed to handle a wide range of vapor concentrations and flowrates. Due to the transient nature of unit vapor deinventory, manned operation of the VCUs is required. In many cases, the vapor destruction in such units is greater than 99.9% and provides regulatory compliance with refinery emission standards.

Liquid scrubbing. This process can be used to remove toxic acid gases, such as H_2S, hydrofluoric acid (HF) and ammonia (NH_3), which would present safety and air-emissions compliance issues if released directly to the atmosphere or thermally combusted, producing acid gases such as SOx, HF or NOx. Liquid scrubbing provides a mechanism wherein vapor contacts a liquid caustic or other chemical solution and undergoes a chemical reaction in which the acid gases are removed from the vapor stream and converted into less toxic salts or other compounds that remain. Post-scrubbing acid-gas vapor

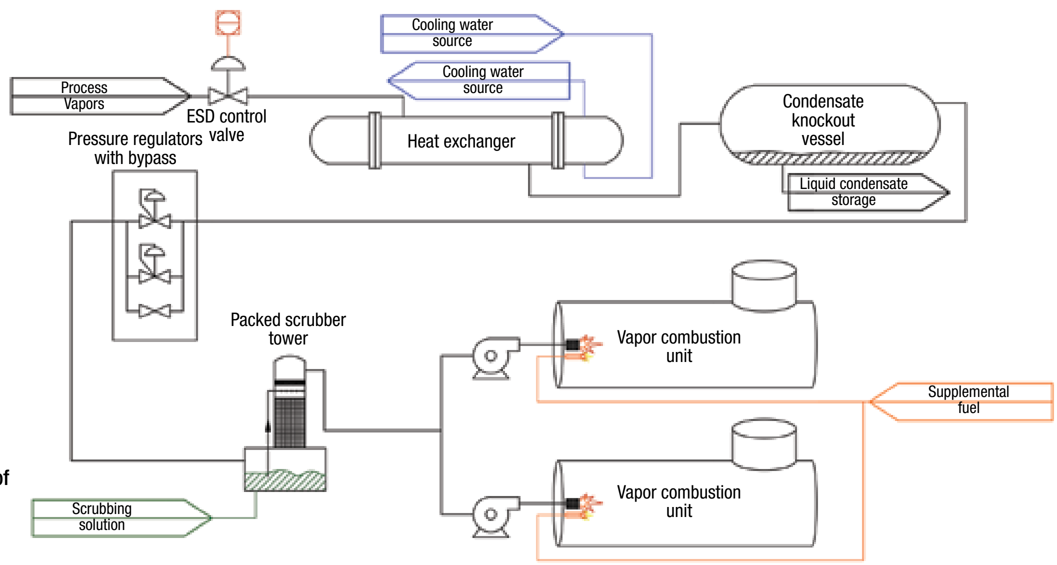

FIGURE 5. This process flow diagram shows a typical layout of several vapor-control systems in a refinery turnaround

concentrations of less than 10 parts per million (ppm) are achievable under proper operating conditions. Figure 4 shows portable liquid H_2S scrubbing equipment. Liquid scrubbing can also remove hydrocarbons or VOCs from vapors using liquid solvents or chemistry in certain applications.

Heat exchanger cooling and condensation. Cooling and condensation in heat exchangers are also important processes during unit vapor deinventory. In some cases, elevated temperatures or steam may exist in the vapor stream, usually during the unit hydrocarbon clearing and chemical cleaning phases. Vapor temperatures as high as 400°F can be encountered during reactor purging. These conditions can cause problems for FGRUs and vapor processing systems. To mitigate these issues, the vapor is cooled to temperatures below 150°F using shell-and-tube heat exchangers, and any resultant condensable hydrocarbon or steam is collected and removed to storage.

Controlling pressure. Pressure control of the vapor stream during the deinventory phase is of critical importance when variable unit pressures need to be managed to ensure proper vapor-control system pressures, which are typically less than 10 psi. With unit pressures as high as 300 psi, pressure reduction using regulators and control valves becomes an essential part of the overall vapor-control system operation and process design.

A typical process flow diagram and refinery site layout for these equipment and components is shown in Figure 5. Figures 6 and 7 illustrate temporary vapor-control systems installed into units undergoing turnarounds.

FIGURE 6. Even if facilities are in full compliance during normal operations, non-regular tasks like turnarounds may necessitate additional, temporary vapor-control schemes to meet new emissions-control regulations

FIGURE 7. Mobile vapor-control systems are an effective way to ensure environmental compliance during non-routine operations, including shutdowns and startups

These vapor-control processes can be integrated into the facility shutdown plan and regulatory compliance program.

Chemical cleaning

Another critical challenge of the turnaround deinventory process is posed by process-unit liquids deinventory and chemical cleaning. Chemical cleaning is a critical part of unit decontamination — it is required in order for the unit to be opened to the atmosphere and components to be removed for further cleaning and repair. It accelerates the unit vapor-control completion timeline by removing sources of hydrocarbons inside the unit, allowing vapor concentrations to be reduced to safe levels more rapidly.

These processes also pose vapor-control challenges due to the potential to emit hydrocarbons, and therefore must be included into the vapor-control strategy. This involves coordinated vapor-control planning and execution with the facility, as well as the chemical cleaning contractor.

Planning, design and compliance

A collaborative vapor-control approach used to develop the best strategy may include the following activities:

- Proper engagement of refinery operations, environmental and maintenance teams with relevant third-party vapor-control and chemical-cleaning providers
- Evaluation of the turnaround unit-deinventory project scope
- Development of a detailed schedule and timeline
- Preparation of written procedures, process flow diagrams (PFDs), piping and instrumentation diagrams (P&IDs) and contingency plans
- Involvement in the management of change (MOC) and process hazard analysis (PHA) processes
- Assessment of regulatory compliance permitting, monitoring and reporting

The engagement of multiple facility departments and contractors under one emissions-management process allows for streamlined communication and compliance execution during multiple phases of the turnaround. This enhances safety and operational performance, schedule reliability, cost accountability and regulatory compliance for the vapor-control activities.

In summary, many refineries are being faced with challenges in performing unit shutdowns and startups under newly enacted regulatory requirements. In many cases, the unit shutdown is being performed for the first time under new regulations and no historical process or procedures are available to follow. Updated timelines and budgets incorporating these new requirements must be prepared.

Early engagement of refinery operations, environmental, maintenance and planning personnel, along with experienced refinery turnaround vapor-control contractors, is of critical importance in establishing a predictable deinventory timeframe and budget. The unit deinventory phase sets the pace for the maintenance portion of the turnaround, and incremental time and cost savings on the front-end can help with the overall turnaround performance. ■

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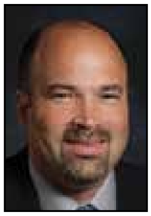
Authors



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Energy Recovery in Compressed Air Systems

Users of compressed air can take advantage of heat recovery to enhance their sustainability, improve energy efficiency and reduce system lifecycle costs

Deepak Vetal
Atlas Copco

IN BRIEF

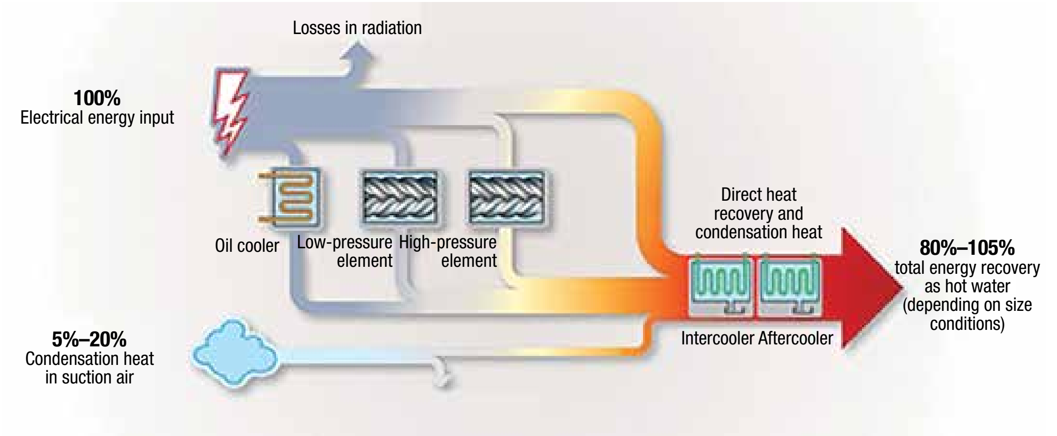


FIGURE 1. An energy recovery scheme can help to utilize waste heat for hot water, which can be used in a variety of process applications

Air compressors account for a considerable portion of industrial energy consumption, and facilities that employ large-scale air compression units are increasingly concerned with optimizing their energy use. Because it is used everywhere, compressed air is often referred to as the industry's fourth utility after water, gas and electricity. Although air may be free, compressed air is not. Therefore, finding the most efficient solution for delivery of compressed air should be a top priority, in addition to increasing the energy efficiency throughout the entire air-compression installation — from supply to distribution to final use. This article looks at the ways that energy management — specifically through the effective application of energy-recovery efforts — can benefit operators of air compressors.

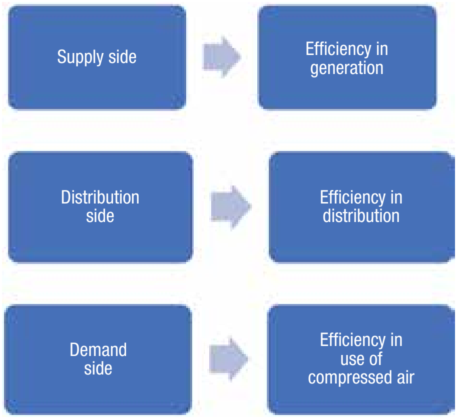
Where to begin

There are numerous guidelines and standards developed by groups like the International Organization for Standardization (ISO; Geneva, Switzerland; www.iso.org) that can provide guidance on how to improve a company's overall energy efficiency, but they sometimes require additional clarification to be properly applied. For instance, while the ISO 50001 standard proposes an energy-management system comparable to ISO 9001, ISO 14001 and ISO 1800, this standard alone does not deliver specific rules or targets. However, it does demonstrate how to set up an energy-management system. In turn, engineers are able to identify major contributors to their company's energy consumption. These contributors are referred to as Energy Performance Indicators (EnPIs). The standards also enable users to determine how much they are spending on each EnPI. Engineers can then define the targets for each EnPI and follow up on reaching these goals. Following a management system will help to reduce the overall environmental footprint of an industrial operation, and utilizing an energy-recovery scheme can be an effective way to begin realizing energy-management goals.

Reducing energy consumption

There exists a huge opportunity to reduce energy consumption in compressed air systems, and energy recovery is one way to get

FIGURE 2. Throughout the entire compressed-air installation, energy use can be optimized according to recommendations from ISO 11011



started. Users can recover heat from existing installed compressors or choose to add the heat-recovery component to newly purchased compressors (Figure 1).

ISO 11011 (Compressed Air — Energy Efficiency — Assessment) is a worldwide standard covering compressed-air energy efficiency. It guides users on how to perform a system audit for compressed air units. It is part of ISO 50001.

ISO 11011 focuses on the total compressed air installation, covering the process from the generation of compressed air, through its distribution and eventual end use. This is illustrated in Figure 2.

Energy efficiency is always a top priority and a strong incentive when seeking solutions to further reduce a facility's carbon footprint. A full understanding of a process' needs is required to select the best technology that will realize optimal efficiency in energy recovery throughout all phases of the air-compression process. In the compressor room, users have many solutions available to optimize the air supply by controlling different compressor parameters and looking at opportunities to recover heat from the compression process.

In the lifetime of a compressor, the initial investment and installation of the equipment will account for around 10–15% of the total cost. On average, end users may spend another 10–15% of the cost on maintenance over the compressor's lifetime. The rest, a staggering 70–80%, goes to energy costs. With that in mind, optimizing a machine's energy usage will have a major impact on the installation's total cost of ownership. Consider that a 35% reduction in energy consumption can typically be achieved by exchanging load/unload compressors with variable-speed-drive (VSD) compressors:

- For a 250-kW compressor running for 8,000 hours, the energy cost will amount to roughly $200,000 per year, or $2,000,000 over 10 years, assuming an energy cost of $0.10/kWh
- In the case of a 35% reduction in energy, this will result in a savings of $700,000 over a 10-year period

If an energy-recovery system is also installed, users will save even more. The additional energy savings will come from reduced or excluded fuel consumption, or other energy sources for heating water.

However, energy recovery does not always result in heat, even when heat is required, and often, there may not be sufficient quantities of heat available. The quantity of recovered energy will vary over time if the compressor has a variable load. In order for recovery to be feasible, a relatively stable heat-energy demand is needed. Recovered waste-heat energy is best utilized to supplement energy supplied to the system, so the available energy is always utilized when the compressor is operating.

Heat recovery potential

When compressors are equipped with heat recovery or energy recovery capabilities (Figure 3), users may have several questions that typically include the following:

- How much heat (kW) can be recovered?
- Will the energy recovery system affect the compressor's performance?
- What is the hot water temperature level that can be reached?

Engineers can answer the first of these questions by calculating the energy-recovery potential of their process

FIGURE 3. A compressor with energy recovery capabilities can contribute to overall lower lifecycle costs for the entire installation

using Equation (1), where W is the recovered energy quantity in KWh/yr.

$$W = [(K_1 \cdot Q_1) + (K_2 \cdot Q_2)] \cdot T_R \qquad (\mathbf{1})$$

Where:
T_R = Time of recovered energy demand, or operating time of the compressor per year, h/yr
K_1 = Portion of time energy is recovered when the compressor is loaded
Q_1 = Available coolant power when compressor is loaded, kW
K_2 = Portion of time energy is recovered when the compressor is unloaded, h/yr
Q_2 = Available coolant power, when compressor is unloaded, kW

To produce compressed air, almost 100% of the electrical energy supplied to the compressor is transferred into heat. It is important that units recover as much of this energy as possible to reduce the plant's energy costs and environmental impact.

In air compressors, the electrical energy used to compress air is transformed into heat. However, the electrical energy is not the only source of energy entering the compressor. Humidity is another important form of energy contained in the air entering the compressor inlet. Following compression, this humidity is condensed into liquid as the air is cooled in the intercooler and aftercooler. In the process of cooling this air, the latent heat of condensation is released into the cooling water.

During the process of compressing air, there are several instances where heat is generated and transferred to the cooling water system. Some of the heat of compression is transferred to the cooling water in the compression elements via element cooling jackets. A significant amount of heat is released into the cooling water system in the coolers. The heat removed from the hot oil in the oil cooler is also released into the cooling water system, and some energy is lost through motor inefficiencies and radiation in other components, such as the element, the cooler, residual heat in the outlet air and residual heat of condensation that remains in the outlet air.

If we look at all of these factors, we see that, despite some losses, the net result is an energy output (as hot water) that is typically 90–95% of the electrical input energy. In other words, the energy going into the compressor is made available by the energy recovery system in the form of hot water.

The amount of latent heat of condensation depends on the temperature and relative humidity of intake air. For that reason, the recoverable energy as a percentage of the incoming electrical power is dependent on the compressor's operating conditions. Intake air temperature, relative humidity, water temperature and pressure all play a role.

In typical industrial conditions, recovery units can recover 90–95% of the electrical input power as hot

water, and sometimes even 95% under certain conditions.

In compressors with an energy-recovery option, the cooling water circuit can be modified to guarantee recovery of the highest amount of energy at the highest possible temperature.

For instance, a cooling loop that flows through the oil cooler, compression element jackets and coolers can result in water as hot as 194°F. Also, note that the water temperature can be regulated depending on process requirements.

There are energy-recovery control units available that are designed to transfer the energy recovered from the compressors while offering protection for installed compressors. They feature a control unit that is installed between the compressor and the cooling-water circuit of the end user. With this design, the closed energy-recovery circuit is completely separated from the user's cooling-water circuit.

Oil-free screw compressors can recover the maximum amount of heat because they operate at much higher temperatures than other compressor types

The energy-recovery control unit is able to manage the recoverable energy and water flow of multiple compressors with the total amount of supplied energy limited to the unit's maximum capacity. These systems may come with necessary safety features, including a deaeration system, a pressure relief valve or an expansion valve that controls the water system pressure.

Looking at different technologies

There are many types of compressor technologies used for compressing air, and their energy-recovery potential varies based on their different modes of operation. The sections below describe the heat-recovery capabilities of three major compressor technologies.

Oil-free screw compressors. These compressors can recover the maximum amount of heat because they operate at much higher temperatures than other compressor types. Therefore, it is possible to recover almost 90–95% of energy, and under some conditions, even more.

Oil-lubricated screw compressors. These units can typically recover 70% of the electrical input energy.

Centrifugal compressors. These machines operate at lower compression temperatures, which limits the amount of recoverable heat. If users try to recover energy from the interstage area, it can create instability due to the dynamic compressor principal, wherein high-velocity air is discharged, converting kinetic energy into static pressure. Centrifugal technology can recover around 30–35% of the electrical input energy.

Another important item to note when considering a heat recovery system is how energy recovery will affect compressor performance. To get the maximum heat recovery, less cooling-water flow passes through the circuit. This results in a higher air-outlet temperature and interstage temperature, which can marginally degrade compressor performance. The rule of thumb states that energy consumption may increase by 3%. It is important to check with the compressor manufacturer regarding compressor performance based on specific input conditions. Keep in mind, if there is a heat-of-compression dryer after the compressor, only 75% of the heat may be available for recovery, as some heat will be used for regenerating the desiccant in the dryer. If you are recovering heat from a VSD compressor, the hot water temperature will depend on the load of the compressor, which can vary.

It is also important to consider other factors, such as the distance between the boiler house and the compressor room, the rate of condensate recovery and the required process temperature.

Industrial plants can take advantage of heat recovery to enhance their "green" credentials, improve energy efficiency and reduce lifecycle costs

How to use recovered energy

Once energy is recovered, users must decide where it will be best utilized as heat. Some of the potential applications for recovered heat energy are described in the following sections.

Preheating feed water. A steam system is never perfect. A continuous supply of fresh cold water is required to compensate for the steam and condensate loss. This process implies that an extra fuel cost is needed to raise the temperature of the cold water, which can be offset by recovering compressor heat.

Process heating. Hot water at a temperature level of 70–90°C (158–194°F) can be used in many industries directly for the process — not just for heating purposes, but also for cleaning, drying, sterilization and more.

Space heating. In some facilities, there is the possibility of turning off the central heating boiler and using the compressor for heating factory halls and office buildings.

District heating. Even if there are no heat consumers in the factory, it is very likely that there are neighboring customers, industrial or residential, who will have a need for heat.

Roasting. To release moisture from solid products, steam is required at temperatures ranging from 110 to 220°C (230 to 428°F), depending on the product.

Tempering. Controlling crystallization of products and ensuring the product's texture and quality require heating, cooling and reheating using hot water.

Heating and tracing. Storage tanks and liquid transfer lines in many processes require heating and heat tracing to ensure product integrity.

Pasteurization or sterilization. Pasteurization and sterilization are used to deactivate microorganisms in products, at different temperature levels and throughput times, depending on the need for refrigeration and shelf life of the product. These applications require hot water or steam, depending on the heat-treatment temperature.

Evaporation. Evaporators are used to concentrate products in the production of milk powder, whey powder, canned products and more. Evaporators may include several passes, or stages, where steam is used.

Cleaning in place (CIP). Automated chemical cleaning systems, which include fixed vessels, valves and transferring lines, use hot water mixed with acids and cleaning agents.

Autoclave processes. Hot water or steam are used in autoclaves for sterilization of dry goods, such as filter housings or hoses, often under vacuum conditions.

With these applications in mind, users of compressed air can begin to consider how energy recovery can best work in their facilities. Almost every industry uses compressors in its plant where heat recovery can be installed. Industrial plants can take advantage of heat recovery to enhance their "green" credentials, improve energy efficiency and reduce the lifecycle cost of the compressed air system. ■

Edited by Mary Page Bailey

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Pitfalls to Avoid When Generating Cost Estimates

The pitfalls in cost estimating that cause project overruns have been well known for decades, yet they continue to plague the CPI

Alfred Chiu
S & B Engineers and Constructors Ltd.

IN BRIEF

CLASS OF ESTIMATE

WISHING DOESN'T MAKE IT COME TRUE

UNDERSTAND YOUR EXPERIENCE

DON'T CHANGE YOUR MIND

KNOW THE PROJECT ENVIRONMENT

THE ESTIMATE GOT A GREAT PDRI

RESOURCES ALLOCATED FOR THE ESTIMATE

When I first started writing this article, I set out to summarize the mechanics of project cost estimation. That was to be followed by a discussion of various management tools, for example Project Definition Rating Index (PDRI) [*1*], that are used to validate the input to the estimate. But it was apparent that there were other factors at play, given the anecdotal and very public records of numerous project delays and cost overruns, that went beyond simply not following a procedure and going through some management check-list gate. As one of the owners ofmy company pointed out in a recent meeting, to Manage With Certainty, one must focus on the input and not just the outcome.

About four decades ago, in my first job with Union Carbide Corp. (UCC), I was given an assignment to find out why many of the plant projects were plagued with delays and cost overrun. In the late 1970s, the Bound Brook plant was suffering from a very tight capital budget constraint. The era was in the mid stage of factory relocation away from the Northeast and mid-Atlantic regions. The conclusions that I drew, after interviewing many of my coworkers at the site, were rather simplistic and seemed to be just common sense. Being a newly minted engineer at the time, I thought it was because I did not fully appreciate the complexity of project execution; and I suppose, so did the senior managers.

Over the years, the problem of project cost and schedule overrun persisted in the chemical process industries (CPI) and the energy sector. It was apparently prevalent enough that many companies were willing to expend scarce resources to hire consultants to work on this riddle. A lot of brain power was being brought to bear on the problem, but it seemed to be more stubborn than that grass stain in the laundry commercial.

FIGURE 1. There are a number of pitfalls one may encounter while following the standard methods for generating a cost estimate

Fast-forward to 2018, in a recent news article, a large public utility company announced another 15% increase in a project's cost, making the current estimate double from the project announcement just four years ago [2]. What happened? Was there some kind of evil mastermind at work? Was it the dreaded tariff? How can a company that is more than fifty years old, working with well qualified contractors, make these mistakes? As most of this cost overrun will likely be borne by the public utility rate payers, the truth of the matter may eventually come to light after some years of investigation. Even then, the fog of project execution will make it difficult, if not impossible, to separate facts from fabrications.

In this article, I assume that the reader can access multiple well-written articles and websites on the Internet [3] that discuss various methods to generate a cost estimate. Instead of delving deeply into the mechanics, this article discusses some of the pitfalls that one may encounter while following those procedures (Figure 1). Hopefully, the reader will find the simple solutions to be easy to apply to everyday project execution. If nothing else, the article may help one sleep better, and it also helps explain how a kitchen remodeling can balloon from $10,000 to $20,000.

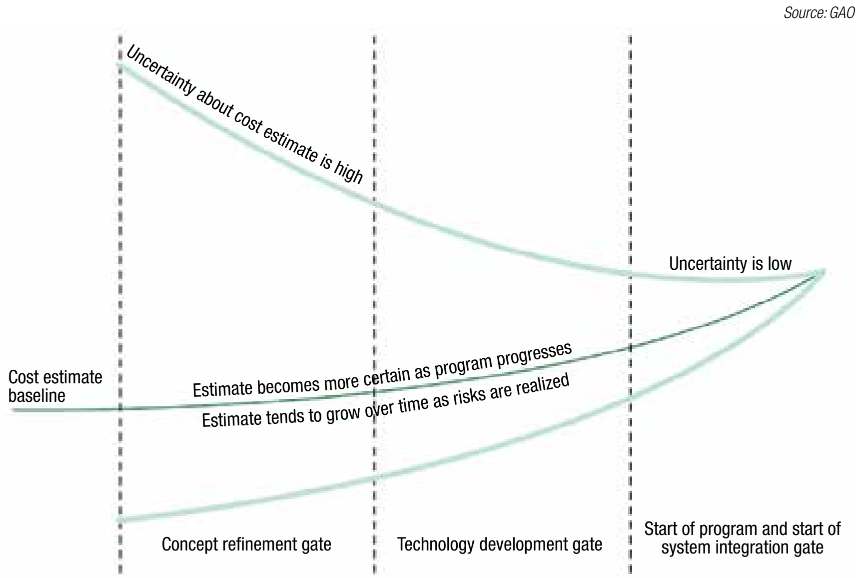

FIGURE 2. As a project develops from the conceptual stage to increasingly detailed definition, the cost estimates and schedule are also progressing in the cone of uncertainty towards smaller probability of error

Class of estimate

The "class of estimate" is a generally accepted term to signify the claimed range of accuracy of cost estimates from one to five [4], the most accurate being one and the least being five. During the development of a project, the estimate accuracy improves as more information is generated to put into the estimating effort. Presumably, the project team is busily checking off those boxes specifying the required inputs. So, if all the boxes are checked, then the estimate must be accurate as defined. There is an often repeated phrase in the information technology (IT) world: "Garbage in equals garbage out."

Beware, just because there is a document transmittal fitting the description, it does not necessarily mean that there is a real contribution to improving the accuracy of the estimate. In fact, it could be quite the opposite. Bad information is invariably worse than no information at all. It is incumbent upon the management team to make sure that the inputs are properly vetted.

The engineering disciplines of the project team must be encouraged to question and evaluate every assumption and calculation. Project management must be encouraged to foster an environment of honesty and openness so that team members can talk about any difficulties encountered. It is also necessary to be realistic and admit, if substantial input is lacking, that the desired objective of estimate accuracy is not feasible.

Wishing does't make it come true

Human nature being what it is, I admit that I still tend to wish my project estimates to be lower and the project schedules shorter. Warning: self-delusion is a very bad way to run a project. It is beyond bad if one is successful in coercing a subordinate or a contractor to abet in that lie.

A friend told me about a meeting with a potential client for a very large project who was adamant about competitively bidding every phase of the work, from front-end loading (FEL) through construction and startup. The logic was that he would easily find the contractor most desperate for his business and therefore give him the lowest price with little or no contingencies and minimal profit margin. He was clearly choosing to ignore the lessons of the time value of money [5], as the schedule would have stretched out more than a year to allow for the bidding process. There was a definite lack of understanding of human nature. What would anyone expect from desperate businessmen trying make their commission or to save their company? If he was not secretly wishing his project to be plagued by endless change orders, he must have optimistically assumed that the contractor estimated correctly or equally unlikely, intended to make up for any overrun out of his own pocket.

The better approach for this client's problem would be to do his homework. First, understand what costs his business plan can support. Second, evaluate the quality of inputs and assumptions that are going into the estimate. Finally, third, delete or revise the scope so that the project cost fits within the economic model. Along the way, he would have found the engineers that he could trust and who would be on board with his objectives.

Along that same line of thought, make a sound estimate and schedule a reality by clearly defining the scope of the project. This scope then drives the discipline details, which are verified with the cost estimator. Note: the ends are not achieved by reducing quality of the inputs and hoping that the estimator can come up with assumptions.

Unfortunately, when the project is driven into a competitive, fixed-cost bidding process, it is not likely that the contractors would reveal the salient information to a project manager. Without it, the project manager is left to scan through the qualifications and exclusions like a first-year law student, perhaps not wanting to believe that the submitted bid is just a book of fiction.

Understand your experience

"I have eaten more salt than the grains of rice that you have eaten," goes a Chinese saying emphasizing the importance of life experience. However, another common saying goes, "If I had a dollar every time a project manager demands to know why an estimate did not match the

FIGURE 3. Why are project costs exceeding estimates?

expectations based on a previous project, I would be a rich man." While a project manager's experience is a prerequisite for the job assignment, he or she must be very careful to balance life experience with the facts on the ground. Building a project in Asia is not the same as building it in Europe, and is not the same on the U.S. Gulf Coast.

Amid the U.S. process industries depression in the mid-1980s, I had occasion to purchase a small pressure vessel that was to be made from Monel. The low bidder was able to deliver the vessel, upgraded to a high nickel alloy, in eight weeks. Due to the unforeseen circumstance, the shop was in possession of the needed alloy materials, which were promptly put to my use. If I were to continue to use that project as my reference, then all the subsequent estimates would have been unreasonably high with long extended schedules.

The combination of wishful thinking and selective memory make a potent brew. The desire to have a project at a certain cost can lead a project manager to question whether the estimator is correct. Instead of approaching an estimate by comparing it to the last project and asking why it can't be cheaper, the first questions that should be asked are as follows:

- What are the inputs and the assumptions that generated these results?
- What are the relative impacts of those assumptions on the bottom line?
- What is the quality of the inputs?

Then, a detailed comparison to the previous project can be made only after ascertaining that the current facts are comparable to the relevant experience. Then, too, the manager's experience should give guidance on what inputs or assumptions are relevant to the problem at hand. Remembering that every project is unique in its place and time allows the project manager to filter out the useful knowledge that can be applied to subsequent work. Otherwise, one could be guilty of comparing apples to oranges.

Don't change your mind . . .

. . . unless you have to. We are bombarded daily from social media that this is a fast-changing world. Constant change is the mantra. As a project develops from the conceptual stage to increasingly detailed definition, the cost estimate and schedule are also progressing in the cone of uncertainty (Figure 2) [*6*]. Assuming the inputs are valid (and this better be true), the probable range of error becomes smaller and smaller with increasing definition and the freedom to make alterations to the overall project scope approaches the vanishing point. Even if one were to be in possession of a perfectly accurate estimate and schedule, changes in personnel, site conditions, or state of the economy, may have a negative impact.

The objective of a project manager is to minimize the changes to the project unless there is an overwhelming reason to do so. The rule should be: "*No changes unless it is unsafe or won't work.*" But when conditions create that reason, the project manager must act aggressively to put everyone on the same page. Then, when all stakeholders agree [*7*], and the negative impacts of changes are understood, the scope change should proceed as quickly as practical. This implies, then, that certain inputs and assumptions that went into producing the earlier cost estimates must be revisited to confirm their validity.

So once again, we emphasize the importance of validating the inputs that go into the estimate. It is also important to periodically revalidate the critical inputs, whether technical, commercial or legal, that are the foundations for the justifications for the project in the first place. With the advent of many upstream and midstream projects in North America, the commercial inputs can quickly change the premise of a project. But at some point, in the execution, an executive management decision will be made to allow a project to go to completion while initiating a follow-up phase.

Know the project environment

Human relationship defies mathematical modeling. Thus, I do not claim to give adequate advice in the area. Nevertheless, in project management, it is necessary to be in alignment with the stakeholders. It should be noted that unless one is aware of the total history of the proposed project, and maybe not even then, care should be taken to avoid challenging the previous conclusions. Unfortunately, for those working on the later part of project development, it means that one may have to settle for less than optimal solutions; or some better idea may never see the light of day. The project manager is still the final arbiter to decide whether certain improvements are needed as the critical factors to maintaining cost and schedule. But these should be discussed with the project team and decided upon one at a time.

I put forward the argument that discretion should always be the governing rule unless the grounds are very familiar. I submit the analogy of a visitor coming into a home and insulting the homeowners. The visitor will most likely not receive an invitation to stay for dinner. On the other hand, it is always necessary to point out that the kitchen is on fire, as that will have greater impact on the overall scheme of things.

Another aspect of the environment is the general uncertainty that is introduced from the imposition of tariffs. In this global economy, there is no doubt that cost increases on material can be expected. The ques-

tion remains to be seen how much it will be. A properly estimated project will have identified the various inputs based on clearly delineated material costs. The project can account for the uncertainty with a modified calculation of the usual escalation factors for each cost item. This number would be summarized below the cost total. Business management would have to decide what level of risk to accept in negotiations, either internal or external, for the project to move ahead.

The estimate got a great PDRI

Business schools teach the importance of measuring performance. As mentioned before, one of the accepted ways of measuring the accuracy of an estimate is by means of the Project Definition Rating Index (PDRI). The methodology is a comprehensive checklist of estimate inputs to which the project team give a completion score: five being not defined, to one being completely defined.

This can be a very effective tool if one is aware of two hidden flaws, both of which can give a deceptively low score. First, while the checklist identifies all of the activities (inputs) necessary to support an estimate, there is no practical way to know if every input is correct. And because the method does not give an absolutely true relative weight to each of the inputs, it is difficult for an outside manager to know which part to focus on. It is up to each discipline lead and the project manager to know whether the input was worth the paper it was printed on.

Second, the PDRI evaluation is done at the end of an estimate effort. It therefore becomes a de facto report card on the project team and specifically the project manager. So, it comes back to that business of human nature and relations. Not being an expert in such matters, I venture a guess that the average project manager would be loath to admit to management or the client (or both), that the time and money spent produced a less-than-perfect product. And at the same time, there will only be scant objections from the project team that does not want to confront their manager.

While discretion is advised on advertising any deficiencies in the input to the estimate, the project manager can utilize the PDRI table to validate the accuracy of these inputs. This evaluation of course, is required while the work is being done and not at the end of the estimate.

Resource allocated for estimate

In an article about the high failure rate of mega projects in the upstream oil-and-gas sector, Edward W. Merrow identified one of the main culprits as being inadequate front-end loading (FEL) being performed [*8*]. I submit that this problem can be just as detrimental to any size project. The lack of an adequate FEL, either because of budget constraints or lack of time, equals poor input to the cost estimate effort. While managers have attempted to plug that gap with "experience", this replacement tool has a very dull blade and should be used with care.

If the FEL effort is bid out as a fixed-cost project, there should be a very detailed listing of the final deliverables, and a plan on how to reach them in the time allocated. The project manager should be careful that the team is not under duress to declare completion without finishing the work, either because of time or budget constraints. If that is the case, then the inputs should be carefully vetted and the claimed accuracy of the estimate appropriately downgraded.

There should be an open communication channel between the discipline leads and the estimating group so that inputs are submitted on a timely basis and the information is useful toward the production of an accurate estimate.

Concluding remarks

The more things change, the more they stay the same. It seems that while technology has revolutionized the way we live, the nature of project management remains the same. The four main reasons for cost overrun given by my colleagues 40 years ago at UCC were:

1. There was not enough effort put into the development of the job scope. Frequently, preliminary process studies turned into full-fledged projects without further development. Subsequently, many project experienced major scope changes.
2. The first point was a manifestation of capital shortage. Management increased effort to conserve cash for project execution. The obvious place to cut was "unproductive" project scoping efforts. This was deemed possible as most of the staff had many years of experience at this plant site. It was more important to get more project authorization applications in the pipeline.
3. Subordinates were reluctant to question project sponsor decisions, even though they know it to be incorrect.
4. In another manifestation of capital shortage and wishful thinking, cost estimates were arbitrarily reduced because "It just can't cost that much." ■

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A Shortcut to Optimize Pipe Diameters by Economic Criteria

This methodology can be used not only for laminar flow, but also for the complete turbulent flow region

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In recent decades, the impact of energy costs on the transport of fluids has led to a significant reduction in fluid velocity and an increase in the diameter of the pipeline. In this article, an improved shortcut methodology is presented for estimating the optimal diameter of pipelines. Besides the laminar flow regime, the algorithm can be applied, for the first time, to the complete turbulent flow region. Several examples are presented that demonstrate the simplicity of the method and illustrate the impact of changes in economic parameters on the optimal diameter of pipelines. Moreover, a sensitivity analysis was done to show that the optimization model provides the solution in an acceptable range, especially for the conceptual phase of projects, as well as for basic design.

NOMENCLATURE

- A Parameter, see Equation (14)
- a Amortization parmeter, \$/yr)
- B Parameter, see Equation (15)
- b Maintenance costs, \$/yr
- C_c, Annual capital cost, \$/yr
- C_e Annual operational cost of pipeline, \$/(W·h)
- c_{en} Cost of electric energy, \$/(W·h)
- D Pipe inner diameter, m
- D_{opt} Optimal pipe inner diameter, m
- E Overall efficiency of pump, compressor or fan
- F Parameter for cost of fittings, valves, erection
- G Mass flowrate of fluid, kg/s
- J Ratio of minor pressure losses and friction pressure drop
- L Pipe length, m
- P Pumping power, W
- P_c Pipeline purchase cost, \$
- Δp Pressure drop, Pa
- Δp_{fr} Friction pressure drop, Pa
- Δp_{ml} Minor pressure losses, Pa
- Re Reynolds number
- R_r relative pipe roughness
- V Volumetric flowrate, m^3/s
- X Parameter that depends on pipe material
- x Parameter that depends on pipe thickness
- Y Plant attainment, h/yr
- η Fluid viscosity, Pa·s
- ρ Fluid density, kg/m^3
- ξ Friction factor
- v Average fluid velocity, m/s

Background

Engineers that work in the chemical process industries (CPI) in fields such as process engineering, oil-and-gas engineering, heating, ventilation and air conditioning (HVAC), thermal and hydroelectric power and related disciplines, quite often perform calculations for pipeline-system transportation of fluids. Fluids flow through plant equipment including reactors, separators, heat exchangers, boilers, tanks, radiators and other devices that are connected by pipes or channels. In this article, we will consider only continuous steady-state transport of fluids.

In order to ensure adequate transport of fluids through the plant, engineer have to select, determine or define the following:

- The route of the pipelines
- The type and size of each pipe (diameter, length and wall thickness)
- The types and sizes of necessary fittings, valves and other accessories
- The types of flowmeters
- The types and basic parameters of pumps, compressors, blowers or fans
- The types of materials for all elements of the transport system (pipes, ducts, fittings, electrical machinery, valves and so on)
- The type and size of pipeline supports and compensating elements
- Transportation safety measures, which can be reduced to stress calculations, testing before and during the commissioning, implementation of protective measures in order to prevent negative external impacts on the transportation system and action taken in order to protect the environment from possible failures of the transport system
- Economic optimization of transport systems in order to reduce the overall costs

Aforementioned elements of design are usually done after design of the basic equipment needed for the process. Some of the listed parameters will be analyzed in more detail.

The most important elements relating to the pipeline transport of fluid are as follows:

- Transportation capacity that should meet the technical and other requirements of all consumers that are supplied with fluids
- Selection of appropriate pumps and other machines needed for the transport of fluids in order to achieve the necessary pressure head
- Choice of materials for the pipeline or channel and pumping devices taking into account the impact of fluid on materials and possible degradation of the material due to erosion, corrosion and cavitation
- Possible accumulation of liquids or solids in the pipeline
- Occurrence of vibration and noise
- Transport safety that can be tantamount to mechanical calculations, tests before and during the commissioning and implementation of protecting measures against external impacts, as well as actions to protect the environment from possible failures of the pipeline transport system
- Economic optimization of the pipeline transport system, which is done in order to reduce transport costs

Economic criteria is, in most cases, crucial for the design of plants, so the optimum size of the series of units that the plant consists of provides the lowest life-cycle cost of any project. The cost of piping typically

represents up to 35% of plant capital cost [1]. Fluid pumping cost is also an important part of plant operation cost. According to the U.S. Dept. of Energy (DOE), 16% of a typical facility's electricity costs are involved with pumping of fluids [2]. It is therefore useful to design the piping system as close as possible to the optimal value, in order to minimize the sum of the capital and operating expenses.

Mathematically rigorous methods for selecting pipe diameters are time-consuming because they involve detailed (iterative) procedures to determine the minimum capital and operating costs. Simple equations, like the one proposed in this article, can provide reasonably accurate estimates of optimal pipe diameters in the initial stages of a plant design, which are a good starting point for a more rigorous procedure.

The first pipe economic optimization model was published in 1937 for turbulent flow in hydraulically smooth pipes [3] and three years later the model was broadened for laminar flow [4]. These models are widely cited in literature and they even became classic university lectures [5]. Recently, a new model was published for hydraulically rough pipes [6].

This article contains new and simple models for economic pipe sizing for laminar, turbulent and transitional flow.

Pipe optimization model

Pipeline cost consists of two parameters: capital cost and operational cost. The most economic pipe diameter will be the one which gives the lowest annual cost.

Pipe purchase cost (P_c) can be expressed as Equation (1):

$$P_c = X \cdot D^x \cdot L \quad (1)$$

Where:
D = pipe inner dia. (I.D.), m
L = pipe length, m
X = a parameter that depends on the type of pipe material
x = a parameter that depends on the pipe-wall thickness (pipe schedule)

The annual capital cost (C_c, \$/yr) of a pipeline is calculated using Equation (2):

$$C_c = X \cdot D^x \cdot L \cdot (1+F) \cdot (a+b) \quad (2)$$

Where:
F = a factor that includes the cost of valves, fittings and erection
a = amortization or capital charge (annual)
b = maintenance costs (annual)

The power required for fluid pumping (P, W) is given by Equation (3):

$$P = \frac{V \cdot \Delta p}{E} = \frac{G \cdot \Delta p}{\rho \cdot E} \quad (3)$$

Where:
V, = volumetric flowrate of fluid, m^3/s
ρ = fluid density, kg/m^3
Δp = pressure drop, Pa
E = overall efficiency of the pump, compressor or ventilator
G = mass flowrate of fluid, kg/s

$$G = V \cdot \rho \quad (4)$$

Energy loss in the pipeline includes fluid friction loss, but also potential and kinetic energy losses. This model excludes the latter two losses since the pumping height is always a fixed value and fluid density is considered to be constant. This means that the pressure drop can be calculated as the sum of the friction pressure drop (Δp_{fr}, Pa) and minor pressure losses (Δp_{ml}, Pa):

$$\Delta p = \Delta p_{fr} + \Delta p_{ml} \quad (5)$$

Weisbach [7] proposed in 1845 the equation that is still in use for pressure drop calculations:

$$\Delta p_{fr} = \xi \cdot \frac{L}{D} \cdot \frac{\rho \cdot v^2}{2} = \frac{8}{\pi^2} \cdot \xi \cdot \frac{L \cdot G^2}{\rho \cdot D^5} = \frac{8}{\pi^2} \cdot \xi \cdot \frac{L \cdot \rho \cdot V^2}{D^5} \quad (6)$$

Where:
ξ = friction factor coefficient
v, = average fluid velocity, m/s

Minor pressure losses can be estimated either as head losses or by using equivalent lengths. In further analysis, the minor pressure losses will simply be taken into account as:

$$\Delta p_{ml} = J \cdot \Delta p_{fr} \quad (7)$$

where J is the ratio of minor pressure losses and friction pressure drop.

Pressure drop then becomes:

$$\Delta p = \frac{8}{\pi^2} \cdot \xi \cdot (1+J) \cdot \frac{L \cdot G^2}{\rho \cdot D^5} \quad (8)$$

Strictly speaking, Equation (8) applies only to incompressible isothermal flow. In engineering practice, this equation can be accepted for the compressible flow if the total pressure drop is less than 10% of the initial pressure [8].

The annual operational cost of the pipeline (C_e, \$/yr) is:

$$C_e = Y \cdot c_{en} \cdot P \quad (9)$$

which yields:

$$C_e = 8 \cdot \frac{Y \cdot c_{en} \cdot (1+J) \cdot \xi \cdot L}{\pi^2 \cdot E \cdot D^5} \cdot \frac{G^3}{\rho^2} \quad (10)$$

Where:
Y = the plant attainment (annual operating hours or hours of operation per year), h/yr
c_{en} = cost of pumping energy, \$/W·h

Total annual pipe cost is:

$$C = C_c + C_e \quad (11)$$

and, since C depends only on D, the optimum economic pipe diameter can be found by:

$$\frac{dC}{dD} = 0 \quad (12)$$

After differentiation of capital, Equation (2), and operational costs, Equation (10), the general form of the solution for Equation (12) is:

$$D_{opt} = \sqrt[5+x]{A \cdot B \cdot \left(\xi \cdot \frac{G^3}{\rho^2}\right)} = \sqrt[5+x]{A \cdot B \cdot (\xi \cdot \rho \cdot V^3)} \quad (13)$$

Parameter A consists of values that must be presupposed for every single pipeline:

$$A = \frac{Y \cdot c_{en} \cdot (1+J)}{x \cdot X \cdot E \cdot (1+F) \cdot (a+b)} \quad (14)$$

and parameter B shows the influence of pipe diameter on the friction factor:

$$B = \frac{8}{\pi^2} \cdot \left(5 - \frac{D}{\xi} \cdot \frac{d\xi}{dD}\right) \quad (15)$$

In order to obtain the useful shortcut formula for estimation of D_{opt}, the derivative $d\xi/dD$ has to be determined for laminar, critical and turbulent flow. The pipe friction factor, in general, depends on the Reynolds number (Re):

$$\mathrm{Re} = \frac{w \cdot D \cdot \rho}{\eta} = \frac{4 \cdot V \cdot \rho}{\pi \cdot D \cdot \eta} = \frac{4 \cdot G}{\pi \cdot D \cdot \eta} \quad (16)$$

and relative pipe roughness:

$$R_r = \frac{\varepsilon}{D} \tag{17}$$

The friction factor for all cases of flow regimes in pipes can be calculated using [9]:

$$\xi = \frac{64}{Re} \quad \text{for Re} \le 2{,}000 \tag{18a}$$

$$\xi = 0.032 + 0.000052$$
$$(Re - 2{,}000) \cdot (R_r^{0.8} + 0.089)$$
$$\text{for Re} = 2{,}000\text{–}4{,}000 \text{ (18b)} \tag{18b}$$

$$\xi = \left\{-1.8 \cdot \log\left[\frac{7.35 - 1{,}200 \cdot R_r^{1.25}}{Re} + \left(\frac{R_r}{3.15}\right)^{1.15}\right]\right\}^{-2}$$

$$\text{for Re} = 4{,}000\text{–}35.5 \cdot 10^6 \tag{18c}$$

Pipe relative roughness, according to open literature data, is in the range R_r = 0 to 0.0333.

For laminar flow, the explicit solution is B = 3.24, and for other flow regimes, the mean value of B should be estimated after integration. For critical flow, the following applies:

$$B_{mean} = \frac{\int_0^{0.0333}\int_{2{,}000}^{4{,}000} B \cdot dRe \cdot dR_r}{(0.0333-0)\cdot(4{,}000-2{,}000)}$$
$$= 3.86 \tag{19}$$

and for turbulent flow (after setting of the upper limit of the integral to Re = 10^8, which is a value that is of importance to engineering practice):

$$B_{mean} = \frac{\int_0^{0.0333}\int_{2{,}000}^{10^8} B \cdot dRe \cdot dR_r}{(0.0333-1)\cdot(10^8-4{,}000)}$$
$$= 4.34 \tag{20}$$

Our estimation for variables that should be known for calculation of A are presented in Table 1, and the final value is A = 0.00236.

After applying A in Equation (13), one can get $(A \cdot B)^{1/5+x}$ = 0.47 for laminar flow and $(A \cdot B)^{1/5+x}$ = 0.49 for other flow regimes. Therefore, a value of $(A \cdot B)^{1/5+x}$ = 0.48 is adopted for all flow regimes in all of the subsequent calculations.

TABLE 1. PRICES OF ELECTRICITY AND CARBON-STEEL PIPES

Parameter	Value	Parameter	Value
c_{en}, \$/(kW·h)	0.08	F	6.5
x	1.5	$a + b$	0.2
X	330	Y, h/yr	8,760
J	0.5	E	0.6

TABLE 2. CALCULATIONS ACCORDING TO THE "RULES OF THUMB" AND PROPOSED MODEL

Literature	[11]	[12]	[13]	New model
Recommended D, mm	285	279	289	341
v, m/s	2.742	2.871	2.658	1.915
Re	1,077,000	1,102,000	1,061,000	900,000
Rr	0.00351	0.00359	0.00345	0.00293
ξ	0.0269	0.0270	0.0267	0.0255
$\Delta p/L$, Pa/m	422	477	389	164
C_c/L, \$/(yr·m)	75.3	72.8	77.1	98.6
C_e/L, \$/(yr·m)	103.5	116.8	95.3	40.1
C/L, \$/(yr·m)	178.8	189.6	172.4	138.7

Economic flowrate or velocity

Optimal pipe diameter equations can be rewritten in order to estimate the most economic flowrate or velocity for a given pipe diameter. From Equation (13), the optimal mass flowrate is:

$$G_{opt} = \sqrt[3]{\frac{D^{5+x} \cdot \rho^2}{A \cdot B \cdot \xi}} \tag{21}$$

the optimal volumetric flowrate is:

$$V_{opt} = \sqrt[3]{\frac{D^{5+x}}{A \cdot B \cdot \xi \cdot \rho}} \tag{22}$$

and the optimal fluid velocity is

$$v_{opt} = \frac{4}{\pi} \cdot \sqrt[3]{\frac{D^{11+x}}{A \cdot B \cdot \xi \cdot \rho}} \tag{23}$$

Algorithm for solving equations

Equation (13) provides an implicit calculation procedure, since the pipe diameter has to be known in order to obtain the friction factor or vice versa. Solving of Equation (21), (22) or (23) also demands the iterative procedure since ξ is a function of fluid velocity. The easiest way for solving the listed equations is to make the assumption of a fluid velocity or friction factor and then apply an iterative procedure. In case of turbulent flow, no more than three iterations are needed. For laminar flow, no more than five iterations are needed.

Example 1

The authors were recently asked to estimate the optimal diameter of carbon-steel pipeline for liquid methanol at ambient temperature. Methanol flowrate was 500 ton/h, its density is 794 kg/m^3 and viscosity is 0.000576 Pa·s. We adopted the absolute roughness ε = 1 mm as a guess value for the end of pipeline life cycle of 10 years.

Solution. Using the methodology proposed above yields an optimal pipe diameter of D_{opt} = 341 mm, the corresponding velocity is v = 1.915 m/s and pressure drop is $\Delta p/L$ = 164 Pa/m. This corresponds to the total pipe cost of C/L = 138.7 \$/(yr·m).

Rules of thumb from various literature sources give the results presented in Table 2. The value calculated by Equation (13) gives the velocity that is significantly lower than the ones from the cited recommendations. The consequential total pipeline cost is about 30% greater than the one calculated by hereby proposed model. This fact is in good agreement with the conclusion from Ref. 10 about the influence of energy cost on pipe diameter in recent decades.

Example 2

For the next example, consider the flow of bitumen through a carbon-steel pipeline with D = 82.5 mm, with volumetric flowrate of V = 20 m^3/h. At 150°C, the density of bitumen is ρ = 959 kg/m^3 and the viscosity is η = 0.407 Pa·s. What is the optimal pipe diameter and what savings can be obtained after replacing the existing pipeline with the optimal one if the length of pipeline is L = 1,000 m?

Solution. According to Equation (13), the optimal pipe diameter is D_{opt} = 110 mm (v = 0.585 m/s, Re = 152, ξ = 0.422) and pressure drop is Δp = 9.44 bars.

For further analysis, we have used the standard steel pipe DN100 (O.D.

TABLE 3. SENSITIVITY ANALYSIS OF PARAMETERS

Parameter	Range of Variation
Production rate	±20%
Fuel/energy cost	–50% to +100%
Capital investment	–20% to +50%

= 114.3 mm, I.D. = 107.1 mm). Using Equations (2) and (10), capital cost is C_c = 17,350 \$/yr, operational costs are C_e = \$6,820/yr, so the total cost is C = \$24,170/yr. For D = 82.5 mm, the pipeline total cost is C = \$31,090/yr. This means that, after replacement, each year the savings will be \$6,920, and the investment will be paid off after 4.5 yr.

On the other hand, recommended velocities and pressure drops from the literature are: 0.6–1.0 m/s in Ref. 14, 0.9–1.2 m/s and 450 Pa/m in Ref. 13, 0.2–1 m/s in Ref. 15, 0.9–1.5 m/s in Ref. 16 for viscous oils and pipelines with nominal diameter DN80–DN250. It is obvious that these recommendations are not covering the region of laminar flow, and one can make a serious mistake by following them.

Sensitivity analysis

The economic analysis consists of the following two parts:

1. The investment and cash flows are first calculated using the most probable values of the various factors (this establishes the base case for analysis).
2. Various parameters in the cost model are then varied, assuming a range of error for each factor in turn, in order to provide how sensitive the cash flows and economic criteria are to errors in the forecast figures.

In other words, the basic economic analysis of a project is based on the best estimates that can be made at the moment of design of the system, and a sensitivity analysis is a way of examining the effects of uncertainties in the forecasts on the viability of a project.

The purpose of a sensitivity analysis is to identify those parameters that have a significant impact on project viability over the expected range of variation of the parameter. Ranges of variation of typical parameters are given in Table 3, which is adopted from Ref. 17.

Data from Table 3 suggest the following variation of parameters:

TABLE 4. PIPELINE DIAMETER FOR EXAMPLE 1 AFTER SENSITIVITY ANALYSIS

Parameter	D_{opt}, mm
G = 160–240 t/h	309–370
ε = 0.05–1 mm	310 –341
$a + b$ = 0.1–0.2	341–382
E = 0.6–0.85	327–341
J = 0–2	320–382
c_{en} = 0.04–0.16 \$/(kW·h)	307–382
A = 0.8–1.5 of basic A	300–402
Mean value	316–371

- G should be in the range 0.8 to 1.2 of basic G
- c_{en} should be in the range 0.5 to 2 of basic c_{en}
- A should be in the range 0.8 to 1.5 of basic A

Furthermore, for the shortcut model presented here, we should include the following:

- The factor of minor losses in the range J = 0 to 2
- Pump efficiency from E = 0.6 up to E = 0.85
- $a + b$ in the range 0.1–0.20
- R_r should be taken into account for new, as well as for old pipes — for carbon steel pipes ε = 0.05–1 mm

Let's reconsider Example 1. After consideration of the sensitivity analysis, we get the pipe diameters listed in Table 4.

In this case, the mean value of the pipeline diameter is in the range D_{opt} = 316–371 mm, which is a variation of less than ±10% of the pipe diameter of D_{opt} = 341 mm obtained in Example 1. Following the data from Table 4, for this example, one can conclude that the variation of pipe diameter is not significant due to the (very strong) exponent 5 + x = 6.5 in Equation (13).

Concluding remarks

The simple optimization model of pipe diameter presented here is suitable for both laminar and turbulent flow. The sensitivity analysis shows that the optimization model can provide the solution in an acceptable range that is especially suitable for the conceptual phase of projects, as well as for the basic design. ■

Edited by Gerald Ondrey

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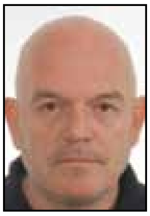

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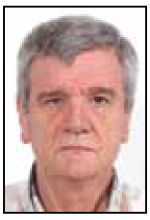

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Recommended Fluid Velocities in Pipelines

The recommended velocities for fluids' transportation must be updated periodically to obtain the optimum value of the pipe diameter in the current economic conditions

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To arrive at the optimum diameters for pipes, the heuristic criteria of recommended velocity has been used in the past. However, the values used as criteria are not updated frequently, despite changes and fluctuations in the economy. Because the recommended velocities are likely out of date, the resulting pipe diameter values can be far from reality.

In the article "Updating the rules for pipe sizing" [*1*], an update of the recommended velocity was presented, based on the energy costs from 2008. This analysis showed that the recommended velocities are highly sensitive to energy and material costs. In this article, the recommended velocities have been updated based on 2017 prices for energy and current prices for highly used materials in the industry.

Optimizing the pipe diameter

Given the uncertainty of fossil fuel depletion and the volatility in its prices, there is a growing general necessity to optimize processes in an effort to locate economic alternatives where operating and investment costs converge to a minimum that increases efficiency. One way to reduce costs in process plants is to optimize the variables that affect the transport of fluids. For example, pumping systems (pumps, motors, pipes and fittings) represent a high operational cost; they account for between 25 and 50% of energy use in certain plant operations. This cost is directly related to the diameter of the pipe.

As presented below, the optimization of pipe diameters can be accomplished using equations that relate the recommended velocity of fluids and the cost of energy.

To determine the recommended velocities and compare what was published 10 years ago [*1*] to 2017, Equation (1) is used. It is presented in Ref. 2. For the calculation of the recommended velocities, Equation (2) is used. As shown in Equations (1) and (2) and Table 1, velocities are intrinsically related to the properties

TABLE 1. OPTIMUM EQUATION

$$D_{opt} = \left[\frac{1.32 C_e Q^{2.84} h \mu_c^{0.16} \rho^{0.84}}{P'(a+b)(F_r+1)XE}\right]^{\frac{1}{P'+4.84}} \quad (1)$$

$$V_{recom} = \frac{Q}{\left(\frac{\pi}{4}\right) * D_{opt}^{2}} \quad (2)$$

TABLE 2. VARIABLES INVOLVED IN EQUATIONS (1) AND (2)

Parameter	Description	Unit
D_{opt}	Optimal diameter of pipeline	in.
v_{recom}	Recommended velocity	ft/s
C_e	Cost of electricity	$/kW h
Q	Volumetric flow	ft^3/s
h	Operating hours per year	h
μ_c	Fluid viscosity	cP
ρ	Density of fluid	lb/ft^3
P'	Slope of logarithms of costs per ft versus pipe dia.	Dimensionless
a	Fractional annual depreciation on pipeline	%
b	Fractional annual maintenance	%
F_r	Factor for installation	%
X	Unit cost of 1 ft of 1-in.-dia. pipe	$/ft in.
E	Efficiency of pump and motor	%

TABLE 3. COST OF ELECTRICITY IN 2017

Month	$/kWh
January	0.0657
February	0.0663
March	0.0674
April	0.0660
May	0.0681
July	0.0733
Average	0.0678

TABLE 4. VALUES FOR EQUATION (1)

Parameter	Value
C_e	0.0678
h	8760
a	0.1
b	0.045
F_r	0.17
E	0.75
Q	0.557

TABLE 5. VALUES OF PARAMETERS X AND P' BY TYPE OF MATERIAL

Parameter	Aluminum Sch. 40	A106 Gr. B Sch. 80	A53 Gr. B Sch. STD	Brass Sch. 40	Cu-Ni Class 200	A312 304L Sch. 40S
X, $/(ft*in.)	19.92	27.02	2.39	30.70	20.40	20.50
P'	0.713	0.450	1.266	0.898	1.116	0.898

TABLE 6. CALCULATION DATA FOR LIQUID PHASE

T, °F	ρ, lb/ft^3	μ_c, cP
32.0	64.04	1.750
50.0	63.58	1.300
60.0	63.30	1.120
80.0	62.81	0.858
122.0	61.69	0.544
150.0	60.93	0.426
212.0	59.18	0.279
220.0	58.94	0.267
225.0	58.79	0.260
225.4	58.78	0.259

TABLE 7. CALCULATION DATA FOR VAPOR PHASE

T, °F	ρ, lb/ft^3	μ_c, cP
225.5	0.047	0.0123
248.0	0.046	0.0128
300.0	0.043	0.0140
392.0	0.038	0.0161
550.0	0.032	0.0197
626.0	0.030	0.0215
800.0	0.026	0.0254
1,000.0	0.022	0.0299
1,100.0	0.021	0.0322
1,200.0	0.019	0.0345

FIGURE 1. The graphs shows the average cost of electricity for the U.S. for 2015–2017

TABLE 8. COMPARISON OF BASE DATA IN THE LAST TEN YEARS

Parameter		A53 Gr. B Sch. STD		A312 Gr. 304L Sch. 40S		Aluminum Sch. 40		Brass Sch. 40	
		2008	2017	2008	2017	2008	2017	2008	2017
X	\$/ft·in.	6.61	2.39	30.70	20.50	22.26	19.92	32.3	30.70
C_e	U\$D/ kW*h	0.070	0.068	0.070	0.068	0.070	0.068	0.070	0.068
h	h	8760	8760	8760	8760	8760	8760	8760	8760
$(a + b)$	-	0.200	0.145	0.200	0.145	0.200	0.145	0.200	0.145
F_r	-	0.170	0.170	0.170	0.170	0.170	0.170	0.170	0.170
E	-	0.50	0.75	0.50	0.75	0.50	0.75	0.50	0.75
Q	ft^3/s	0.557	0.557	0.557	0.557	0.557	0.557	0.557	0.557

of the fluid and a series of economic parameters, including energy costs, pipe materials and other operational criteria. All variables are given in Table 2.

U.S. energy cost variation

Because the determination of optimum diameter is strongly related to the cost of energy, Figure 1 shows the variations in the cost of electricity for the industrial sector in the last two years and Table 3 shows the average cost of electricity in recent months [*3*]. Figure 1 indicates that the price of electric power in the U.S. has remained technically constant, with a maximum variation of 10.0% compared to the average. To obtain the cost of electric power (C_e) needed for Equation (1), the cost of electric power for the U.S. industrial sector was averaged from January to July 2017. That information is shown in Table 2.

Table 4 shows the values of the parameters to be used in Equation (1). In addition, values of parameters X and P were obtained for six of the most commonly used materials in the chemical and petrochemical industries. The costs of these materials were obtained from international suppliers and were analyzed in particular. The materials analyzed are listed below:

- Aluminum schedule-40
- Brass schedule-40
- Carbon steel A106 grade B, schedule-80
- Carbon steel A53 grade B, schedule-STD
- Copper-nickel class 200
- Stainless steel A312 Grade 304L, schedule-40S.

Table 5 shows the values of X and P by the type of material analyzed. These were obtained from pipe quotes found on Internet sources and from Producer Price Indexes (PPI) [*4*].

Calculation protocol

The behavior of the recommended velocities was compared using the density and viscosity at different temperatures, for each of the materials, keeping the pressure constant at 19.10 psia. The fluid used for the calculation was water.

Table 6 shows the values used in the calculations for the liquid phase. For each temperature mentioned in Table 5, the recommended velocities in the liquid phase were obtained for different densities (Figure 2) and different viscosities (Figure 3) for each material. Table 7 shows the values used for the calculation for the liquid phase. And for each temperature mentioned in Table 6, the recommended velocities in the vapor phase were obtained, also with varying density (Figure 4) and viscosity (Figure 5), for each material.

The order of recommended velocities, from greatest to least, is the following for both phases (liquid and vapor): Brass schedule-40 and copper-nickel class 200 > Stainless steel A312 grade 304L, Schedule-40S > Carbon steel A106 grade B, schedule-80 > Aluminum schedule-40 > Carbon steel A53 grade B, schedule-STD.

The order above indicates that the most expensive materials will have the highest recommended velocities and the smallest diameters, and vice versa. However, it is important that, with regard to the service being handled, the most appropriate material is selected.

TABLE 9. VARIATION OF MATERIAL COSTS 2008–2017

Parameter	*X*, \$/ft·in.		Variation, %
	2008	2017	
A53 Gr. B Sch. STD	6.61	2.39	176.6
A312-304L Sch. 40S	30.70	20.50	49.8
Aluminum Sch. 40	22.26	19.92	11.7
Brass Sch. 40	32.3	30.70	5.2

Analyzing changes in velocities

To compare the data obtained here with the costs over the last ten years, four materials were selected and analyzed in both cases:

- Aluminum schedule-40
- Brass schedule-40
- Carbon steel A53 grade B, schedule-STD
- Stainless steel A312 grade 304L, schedule-40S

Table 8 shows the influence of the change in energy and material costs over the last ten years, and Table 9 shows the comparison between the costs of materials over the same time period.

The results of the comparative analysis of recommended velocities show that, although the costs of energy (3.24% in the last ten years) and the materials studied have decreased (Table 9), the recommended velocities have increased, making the optimum

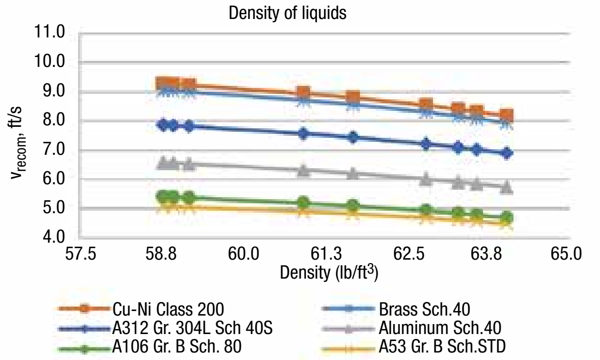

FIGURE 2. The graph shows the recommended velocity versus density of liquids

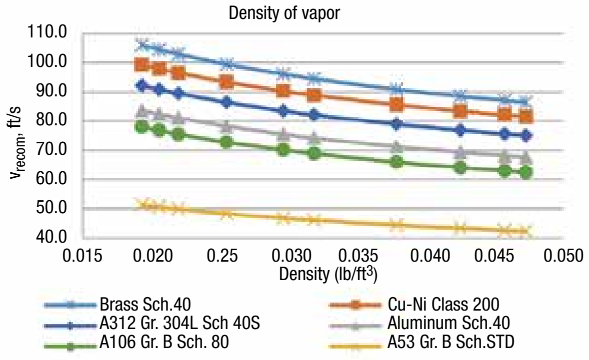

FIGURE 3. The graph shows recommended velocity versus density of vapors

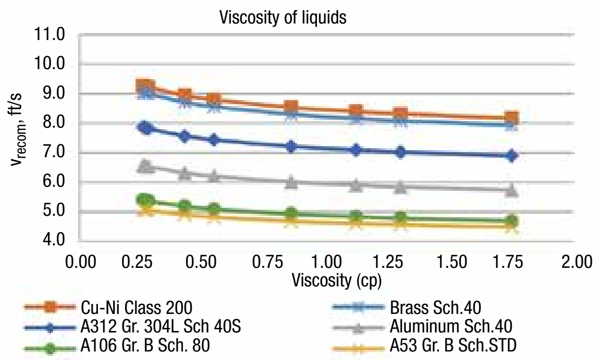

FIGURE 4. The graph shows recommended velocity versus viscosity of liquids

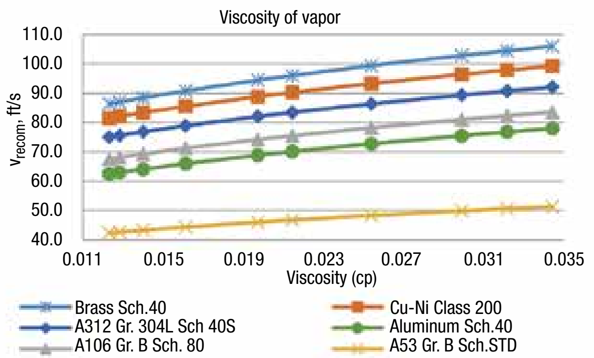

FIGURE 5. The graph shows recommended velocity versus viscosity of vapors

diameters of the pipes decrease by up to 35.0% compared to 2008.

The above result is due mainly to two factors. Required efficiency of pumps and motors increased from 50 to 75%. This is because at present, the design of pumping equipment follows the requirements established in standards such as American Petroleum Institute standard 610, which indicates that operation must be as close as possible to the best efficiency point (BEP), which is the flow at which the pump system is operating its highest efficiency.

Depreciation and maintenance factors have decreased because more control exists over maintenance procedures and standards, so plants can operate for longer times.

Example calculation 1

For this example, the following information and values are used:

- The pipe material is carbon steel A53 grade B, schedule-STD
- Fluid is water at 60°F
- Flow (Q): 1.625 ft^3/s
- Density (ρ): 50.0 lb/ft^3

Using this information, a recommended velocity (v_{recom}) of 4.95 ft/s is obtained, as shown in Figure 6. The cross-section area for these conditions is the following:

$S = Q / v_{recom} = 1.625 / 4.95 = 0.3285\ ft^2$

This cross-section is reasonably close to that of a 8-in. dia. pipe for this material (S = 0.3474 ft^2). Comparing the recommended velocity value that would be obtained with the same data ten years ago (4.38 ft/s), it is observed that the recommended velocity increased by 13.0% and with it, the area of the cross-section increases:

$S = Q / v_{recom} = 1.625 / 4.38 = 0.3710\ ft^2$

Since this value is higher, it is necessary that the tube diameter is 10-in. dia. (S = 0.5475 ft^2) to achieve the required value.

Example calculation 2

For this example, the following information and values are used:

- Pipe material: Stainless steel A312 Grade 304L, Schedule-40S
- Fluid: water at 60°F
- Flow (Q): 1.625 ft^3/s
- Density (ρ): 30.0 lb/ft^3

Using this information, a recommended velocity (v_{recom}) of 8.88 ft/s is obtained, as shown in Figure 6. The cross-section area for these conditions is the following:

$S = Q / v_{recom} = 1.625 / 8.88 = 0.1830\ ft^2$

This cross-section is reasonably close to that of a 6-in. dia. for this material (S = 0. 2006 ft^2). Comparing the recommended velocity value that would be obtained with the same data ten years ago (7.50 ft/s), it is observed that the recommended velocity increased by 18.0% and with it, the area of the cross-section increases:

$S = Q / v_{recom} = 1.625 / 7.50 = 0.2166\ ft^2$

As in the first example, the value of the section is greater, so it is necessary that the diameter of the tube is 8-in. dia. (S = 0.3474 ft^2) to achieve the required value.

Concluding remarks

Revised values for the recommended fluid velocities in this article have proved to be highly sensitive to energy and material costs. However, there are two main factors related to the increase in recommended fluid velocities and the decrease in optimal diameters: increase in the required

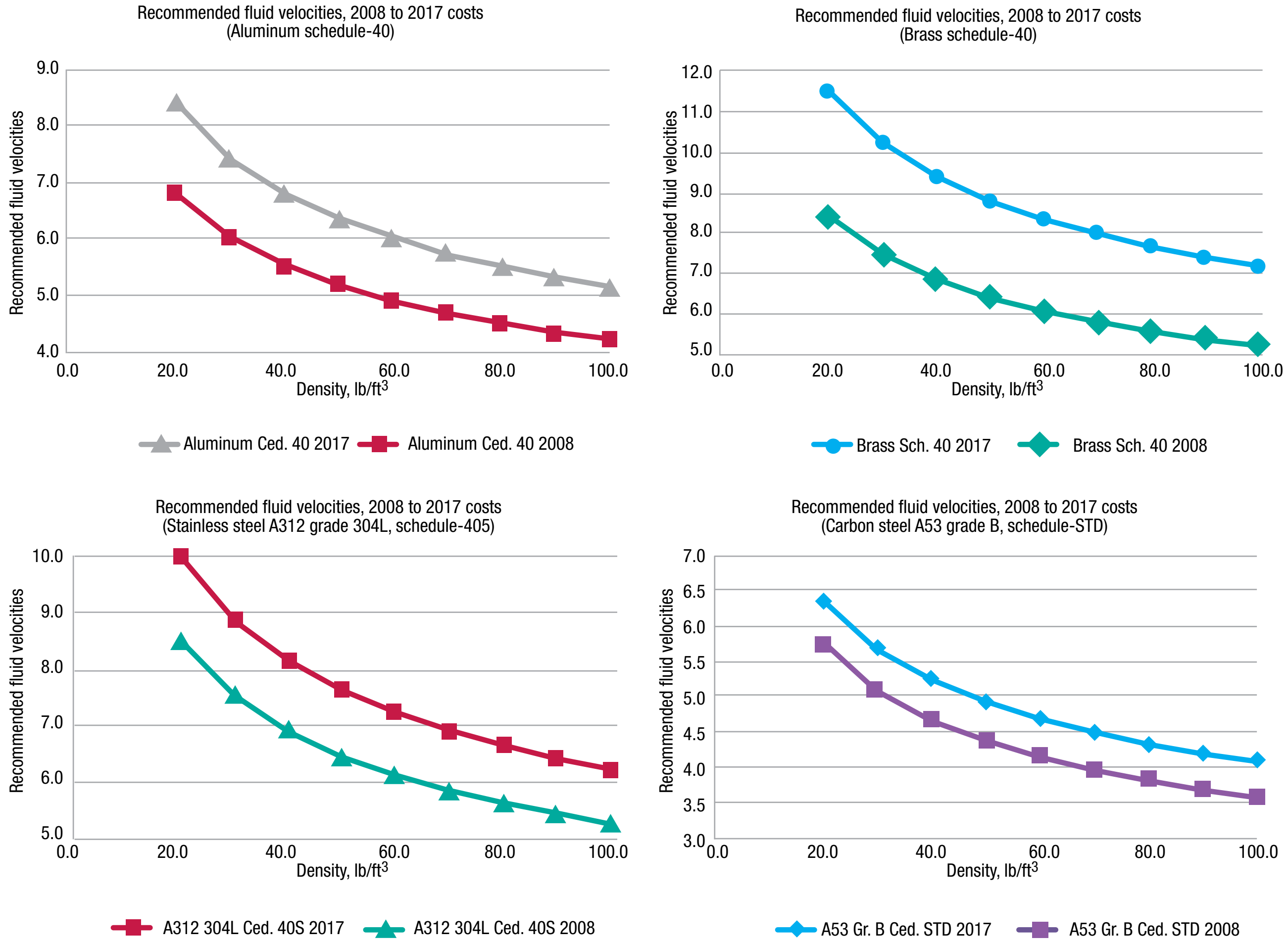

FIGURE 6. Recommended fluid velocities, 2008–2017 are plotted here

efficiency of pumping equipment and decrease in the depreciation and maintenance factors. It is important to remember that these factors have changed due to the application of stricter standards, focused on the efficient use of resources. In general terms, recommended fluid velocities have increased up to 35% due to the decrease in the cost of materials since 2008.

The analysis serves as a guide for the management of fluids at different conditions, while maintaining the integrity of the pipes. So it is important to continue updating the recommended fluid velocities to consider fluctuations in energy and material costs used at least every five years, and maintain an optimal design. ■

Edited by Scott Jenkins

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Engineering & Construction (E&C): Modeling Integration Enables Optimized Execution

As E&C companies strive to develop Building Information Modeling (BIM) 6D models for the owners and operators of CPI facilities, strong efficiency gains benefit all parties

Stephen Wyss
Bechtel Corp.

FIGURE 1. Great efficiencies arise when construction staff can access materials- and project-related information via a model viewer

Truly transformational change is upon the engineering and construction (E&C) industry, and some consider the trends that are occurring today to be enabling the most significant evolution in history. Cumbersome document-based project execution is transitioning to robust, data-centric execution, as innovators seize opportunities in emerging technologies and ongoing expansion in cloud-based environments. E&C contractors that embrace, define and drive change will flourish, while those that dawdle will find themselves in the undesirable position of reacting to change. Several contemporary studies [*1*] document how E&C industry productivity has lagged over recent decades relative to other industries, and identify the catalysts that are driving this change. Collaboration is a dominant theme in the path to increased productivity.

Opportunities for productivity-enhancing collaboration are presenting themselves in many spheres — regulatory, organizational and contractual. Of these, one of the contractual paths stands out — the path to BIM 6D (For more on BIM 6D models, see the sidebar on p. 59).

Once E&Cs evolve their processes as part of this data-centric paradigm shift, they will be able to deliver a BIM 6D model to the owner upon construction completion, populated with relevant building component information, such as product data and details, maintenance and operation manuals, cut-sheet specifications, photos, warranty data, web links to product online sources, manufacturer information and contacts, and more. Data will be accessible via tools (devices and platforms) and from cloud-based data sources, to facilitate operation and maintenance of the facility.

This article distinguishes the regulatory, organizational and contractual aspects of project management and the trends that are driving the path to 6D, and offers recommendations for how E&Cs can use this path to implement paradigm-shifting work process changes that can significantly enhance productivity.

- *Regulatory collaboration* entails proactive public and private partnerships (P3), with parties working together to create and facilitate conducive environments
- *Organizational collaboration* involves E&C entities seizing internal productivity-enhancing opportunities relating to innovative software tools and cloud-based environments, and using these advanced capabilities to redefine the traditional relationships and responsibilities that exist between engineering, procurement, construction and commissioning functions
- *Contractual collaboration* entails parties altering execution and relationships to facilitate information exchange and share risk so as to minimize information-sharing barriers and to be more nimble in implementing executional variation

The drive toward a 6D model

Approximately two decades ago, owner and operators throughout the chemical process industries (CPI) began requiring a 3D model as a deliverable from E&Cs whenever a capital project was handed over for operation. In the near future, E&C contractors can expect to find owners and operators requiring delivery

of a 6D model as the key deliverable with the facility at handover. Why is that?

While a 3D model has historically enabled owner/operator personnel to maintain and update a centralized engineering database of the facility, the delivered facility still came with volumes of documents and manuals produced from a document-centric execution process, and all of those support materials needed to be managed through a centralized control and storage organization. Owner/operator maintenance and operations personnel needed to access key plant information from within this document storage and organization system, whether via hard-copy documents and manuals, or via an electronic data management system (EDMS) — a cumbersome process in either case.

By contrast, a 6D model produced using a data-centric execution process centralizes and streamlines information access for all stakeholders, because it is object-centered, not document-centered. Whereas in a document-centric environment, an operator or technician might need to chain through multiple documents to find the information sought, whether it was a maintenance log of a pump or a list of parts for an instrument, a 6D model with fully developed attributes at the object level — the operator's pump or the technician's instrument — enables that individual to visualize the object (a pump or instrument, in the example above, or any other object) via a model viewer, and directly access linked information from the object through associated attributes.

FIGURE 2. With greater centralization and integration of all project-related data and information, construction personnel can easily check the most up-to-date material test reports from a tablet

Model viewers

During the design phase of a facility, 3D models are constructed using sophisticated design-authoring software tools. These allow the model to evolve as E&Cs design the facility. Parties not involved in the design process, but who have an interest in monitoring the design evolution (such as the procurement staff, construction staff and others), are able to monitor this evolution via the use of model viewers (Figure 1).[1]

Model viewers display the 3D model much the same as the design-authoring software, but do so from a static file that is created on a regular basis (generally daily, with the

1. Examples of model viewers include Intergraph's Smart Plant Review, Autodesk's Navisworks, and CAXperts Universal Plant Viewer

FIGURE 3. The BIM 6D approach leverages a data-centric paradigm shift that allows engineers to move from reliance on disconnected documents, software and databases, toward an approach based on centralized objects, tools and data. These engineers check design specifications from a central location

file compiled overnight). Model viewers are also able to display object, or component, and attribute information associated with that object, to the extent that attributes are defined and data are associated.

Model viewers allow remote staff to view the objects in the facility and drill down to the object sought — say, the pump or instrument above — in much the same way they would do so physically. If they know the generic description of the item, say "demineralized water storage pump," or "hydrogen gas bulk-feed pressure regulator," or have an identifier of the item, such as "WD-MT-001" or "PG-PCV-001," then using the model viewer query functionality, they can drill down to and visualize the object virtually in the model in its adjoining environment, without actually being required to do a site inspection. Alternately, if they know the area of the facility but are not certain of the item sought, they can open the model viewer, drill down to the area sought, and then navigate in the model to find the item sought, just as if they had to do the same physically in the facility.

If the object has a fully developed set of attributes — such as specifications, design data, manufacturer name, manufacturer part number, manufacturer inspection records, constructor installation records, maintenance records — with direct links into an EDMS system that contains associated records, the operator or technician can directly access this information via numerated links in the model viewer without the need to exit the model viewer and access the EDMS system.

Conversely, if the model viewer can be accessed via a cloud-linked tablet (Figure 2), this enables the operator or technician to access the same information standing directly in front of the object — the pump or instrument — and to troubleshoot on the spot, pulling up necessary information, such as inspection records, materials certifications and so on, without having to run back to a centralized work station, or worse yet, to a document-control office. Aside from the reduced time needed to access the information, the improved timeliness associated with making a decision to take an object off line or out of service, particularly when shutdown or safety considerations are involved, allows for better-informed decisionmaking.

6D model rectifies E&C issues

Today's modeling tools provide a strong platform for E&C companies who successfully transition to a data-centric execution process to deliver a 6D model. But there are two huge challenges these contractors face: (1) model scope, and (2) model integration. The greater the challenge, the greater to opportunity — and in both of these challenges lie opportunities that present E&Cs with the opportunity to lead and define change, instead of being left in the dust to react to it.

Model scope. E&Cs have been using computer modeling of facilities for more than four decades, although the first models were not created using software that mimicked a design process, but instead consisted of data input from scaled plastic models. The primary benefits from 3D models have historically been the ability to both produce drawings from the model and perform clash-checks.

As a result, the 3D model scope has historically been limited to inclusion of only those disciplines and objects where the time involved to input model data and associated value was outweighed by detriments associated with manual drawings, specifically the inability to identify clashing attributes and extract data. Electrical bulk materials are a good example. Most E&Cs will model medium- and high-voltage cable and associated raceway, but leave low-voltage wire and cable and small-diameter conduit out of the model. In this scenario, the E&Cs will generally install the low-voltage wiring in the field, and document it using as-built drawings. There are similarities in instrumentation, although most piping and civil/structural materials do end up getting modeled.

The trend is toward modeling more, not less, but until such time as owner and operators require the vast majority of objects in the model, E&Cs will still define model scope based on executional value obtained from modeling objects that are directly related to construction execution. The E&C firm uses the model primarily for engineering personnel to communicate to construction personnel about how to build the facility, and to document the physical facility, inclusive of materials. If the construction craft knows what to do without having it articulated in the model, for example, how to route minor wiring, or how frequently wiring may need cable ties, then there is no value to the E&C to expend resources to include such detail in the model. If the owner/operator states a level of detail to be in the model that exceeds what the E&C sees as value-added, then the E&C will add it. But not unless required to do so.

While it is unlikely 6D models will ever contain actual modeling of every minute object in the facility —

down to the last screw and washer — we can expect that 6D models will eventually model most objects, and when it comes to items such as minor hardware, to have those items still fully detailed in reference data in the model. This includes a list of installation parts that goes with a minor component such as a conduit fitting.

Model integration. Model integration creates the biggest challenge, and the greatest opportunity for E&C productivity enhancement awaits there. Even where an E&C provides the engineering for the entire facility, every facility employs a significant amount of complex equipment contracted from specialized suppliers. Many of these components and systems experience a comprehensive design evolution with a free-standing 3D model of their own. These models will need to be compatible with the model that is produced by the E&C, and eventually integrated into a final 6D model for delivery to the owner/operator.

Such equipment includes fired heaters, heat-recovery steam generators (HRSGs), complex compressors, turbines and more. Meanwhile, when the E&C subcontracts a portion of the design to a subcontractor, or the project is structured as a joint venture, models developed by the different contractual parties will need to be compatible and integrated with the prevailing 6D model, as well.

UNDERSTANDING BIM

Building information modeling (BIM) is a process involving the generation and management of digital representations of physical and functional characteristics of places. BIM files often (but not always) involve proprietary formats and data, and they are typically used to support decisionmaking regarding a building or other built asset.

BIM "dimensions" are defined generically as:

- 3D. This virtual model of the facility uses a variety of authoring tools and contains a graphical user interface with data-capturing techniques
- 4D. This is a 3D model that has been integrated with a time element — specifically the project schedule. This lets users view the model over time as the facility will be erected, and helps to identify conflicts in work areas
- 5D. This is a 4D model that is integrated with cost or resource (quantity) data, enabling users to monitor cash flow, staffing requirements and other material-related requirements
- 6D. This model contains all of the information needed for commissioning, startup, handover, operation, maintenance and management of the facility
- 7D. This model's objects are identified according to risk level, including risk assessments, HAZID/HAZOP, startup, operation and more
- nD. This model incorporates and defines supplemental dimensions, as needed; for instance, in adverse climates objects can be associated with weather-related elements ■

Integration-related challenges

When it comes to integrating models from disparate sources, E&Cs face the following three challenges:

- The 6D data infrastructure must be capable of addressing, storing, and linking all of the requisite data at the object level, without loading up the compiled model with data that are beyond the reasonable ability of the modeling software to process and display
- All parties need to establish processes and protocols related to archiving of data to protect themselves from the current undefined legal status of data until such time as the legal community catches up with related emerging technology and the law becomes settled
- E&Cs need to establish collaborative processes with external parties — including materials suppliers, service suppliers, joint venture partners and more — that facilitate integration of external data, including model data where applicable, so as to deliver a consolidated 6D model

This may sound quite daunting. The first issue above — model capacity — will be resolved via ongoing advances in technological processors. The second issue — the legal status of data — needs time, to allow the legal community to catch up with technology; in the meantime, E&Cs should consult legal counsel to carefully protect themselves in this relatively uncharted area. The third issue — improved collaboration between contractual parties — is where the potential exists for E&Cs to transform the stodgy, historical, iterative design process into a more robust, accelerated design process. E&Cs that are able to establish collaborative design processes with their suppliers, subcontractors, and joint-venture partners will be able to significantly reduce design-related costs and shorten project schedules.

Reduce iterative model design

Design authoring 3D model software allows E&C disciplines such as civil, structural, architectural, piping, electrical and instrumentation systems to evolve the design simultaneously. However, current-state document-centric processes relating to pivotal equipment — primarily mechanical equipment and some instrumentation — force the design process to be iterative, with the core design constantly being impacted by updated supplier data as the equipment design evolves in parallel much the same as the facility design evolves. As noted above, such major equipment includes fired heaters, large compressors, pumps, turbines and more.

In a document-centric design process, these suppliers communicate with the E&C via document submittals. Information is exchanged at key project milestones, at which point the supplier's designs and drawings achieve a certain level of design maturity, and communicate a large amount of information in a block, despite the fact that much of the information may have matured some time ago. These submittals often require the E&C to adjust the design upon receipt of the supplier drawings, and possibly add comments for the supplier on certain unacceptable aspects of the design.

Not only does this cumbersome document-submittal process delay the finalization of the E&C design, but if the submittal results in comments back to the supplier, then the supplier's design experiences a similar iterative impact, which may further impact the core E&C design. Most iterative design changes are small — but they can significantly impact the final piping, design drawings, and have cascading impacts on structural steel and even civil engineering requirements, sometimes causing foundation shifts, which might then

impact related underground electrical and piping facilities.

As E&Cs transition to data-centric execution, a more-streamlined process whereby the contractual parties — the E&C and its major equipment suppliers — exchange information via regular model exchanges will accelerate information exchange. This newer approach offers the potential to completely eliminate the cumbersome document-submittal process, and supports the delivery of a 6D model (Figure 3).

Affected parties have done what they can to optimize the existing, cumbersome document-submittal process — identifying drawings and data to be submitted, and attempting to break up submittals in logical groups of information. But for large, complex equipment, the number of drawings and documents can reach into the hundreds, and there can be dozens of individual submittals of groups of drawings, each of which has the potential to necessitate repetitive submittal.

And these document-submittal processes have required E&Cs to create entire bureaucracies (for instance, dedicated document-control organizations) that manage these submittals. Document control teams receive supplier documents into the document-control systems, whether this is an EDMS or a hardcopy system. For instance, documents are issued out to the responsible engineers, with routing around to all impacted parties, and then received back for incorporation of comments and transmittal back to the supplier — a laborious, error-prone and time-consuming process.

Envision a more streamlined process where the equipment supplier exchanges model updates with the E&C company on a regular basis — at least once each week — and the E&C integrates each model update into the E&C model. The supplier's model objects are assigned attributes for submittal references (inclusive of required submittal dates), supplier design maturity, and E&C approval status, and the supplier re-integrates data from the E&C back into its core model, including acceptance status and critical design comments affecting the supplier design. All of this happens efficiently each time an exchange and update occurs. In such a process, the E&C can identify issues with the evolving supplier design early, and communicate issues back to the supplier via model-attached comments.

Not only does this significantly reduce document-related iteration, but it transforms the design reviews from a cumbersome, milestone-based document-review process to an accelerated data-review process, as the object design matures. In such a scenario, the responsible E&C procurement personnel are charged with monitoring and expediting supplier progress, and they can query the model for a set of data defined as a single submittal, and ascertain if the supplier design is progressing to support the schedule dates.

Similarly, E&C engineering staff can simply execute a similar query once a set of supplier objects has achieved a level of design maturity such that approval is required, and can query the status of the objects in the model, with the status being communicated back to the supplier via the next model exchange. Such a seamless model-exchange process accelerates the exchange of critical information, and completely eliminates the burdensome document-submittal process. Engineering hours are significantly reduced, the schedule is accelerated, the document-control hours are significantly reduced, and the infrastructure for a 6D model is enabled.

Further benefits of a 6D model

This article discusses the benefits of a 6D model to the owner and operator of a capital-intensive CPI project. The same benefits accrue to non-design E&C personnel as they execute their duties, to the extent the information is available in the model at any given time. Procurement specialists, expeditors, quality-related personnel, logistics experts and warehousing personnel can access the model viewer and query individual objects or groups of objects to seek information or status updates, and such information can be easily accessed by purchase order number, work package or any attribute group assigned.

Similarly, using this newer approach, construction personnel will have increased access to data and delivery information to plan work, create work packages and confirm construction readiness. Commissioning and startup teams probably benefit the most, in that documents that they would otherwise need to compile into hand-over packages are all available at the object level, facilitating system startup and handover.

Closing thoughts

The discussion above has focused on the benefits of model integration — enabling improved collaboration — between E&Cs and their major equipment suppliers, not only as a path to BIM 6D, but to significantly increase both the design productivity of the E&C and its major equipment suppliers. There will be similar benefits with minor suppliers that have submittal requirements. And experience gained in integrating models will facilitate model integration from subcontractors and joint-venture partners, leading to the delivery of a 6D model to owner/operators. Clearly, in addition to delivering a 6D model to the owner/operator, E&Cs have the opportunity to realize significant productivity enhancements as they improve their work processes to deliver a BIM 6D model. ■

Edited by Suzanne Shelley

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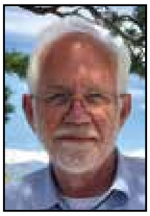

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Economic Indicators

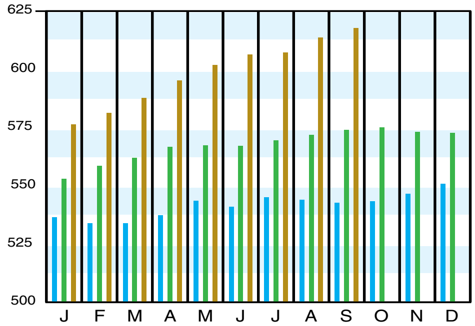
2016 2017 2018

Download the CEPCI two weeks sooner at www.chemengonline.com/pci

CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957–59 = 100)	Sept. '18 Prelim.	Aug. '18 Final	Sept. '17 Final
CE Index	617.8	614.6	574.0
Equipment	753.3	749.8	692.5
Heat exchangers & tanks	671.1	669.3	606.8
Process machinery	731.5	728.1	685.3
Pipe, valves & fittings	980.8	979.8	897.4
Process instruments	422.1	421.2	411.0
Pumps & compressors	1030.7	1029.1	985.0
Electrical equipment	551.0	539.7	521.9
Structural supports & misc.	834.7	826.6	741.8
Construction labor	340.7	336.5	334.3
Buildings	604.0	602.5	564.9
Engineering & supervision	317.2	317.6	309.8

Annual Index:
2010 = 550.8
2011 = 585.7
2012 = 584.6
2013 = 567.3
2014 = 576.1
2015 = 556.8
2016 = 541.7
2017 = 567.5



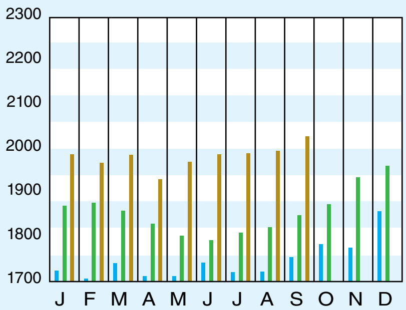
Starting in April 2007, several data series for labor and compressors were converted to accommodate series IDs discontinued by the U.S. Bureau of Labor Statistics (BLS). Starting in March 2018, the data series for chemical industry special machinery was replaced because the series was discontinued by BLS (see *Chem. Eng.*, April 2018, p. 76–77.)

CURRENT BUSINESS INDICATORS

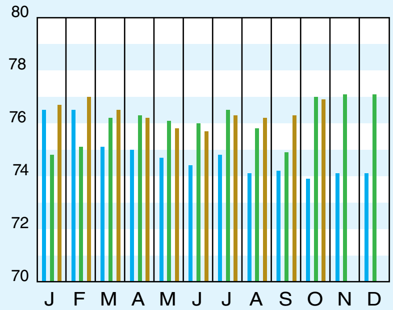
	LATEST		PREVIOUS				YEAR AGO	
CPI output index (2012 = 100)	Oct. '18	= 103.4	Sept. '18	= 102.7	Aug. '18	= 102.9	Oct. '17	= 101.1
CPI value of output, $ billions	Sept. '18	= 2,030.9	Aug. '18	= 2,008.6	Jul. '18	= 1,991.3	Sept. '17	= 1,809.0
CPI operating rate, %	Oct. '18	= 76.9	Sept. '18	= 76.4	Aug. '18	= 76.6	Oct. '17	= 75.9
Producer prices, industrial chemicals (1982 = 100)	Oct. '18	= 287.7	Sept. '18	= 278.8	Aug. '18	= 279.1	Oct. '17	= 258.5
Industrial Production in Manufacturing (2012 =100)*	Oct. '18	= 105.4	Sept. '18	= 105.1	Aug. '18	= 104.8	Oct. '17	= 102.6
Hourly earnings index, chemical & allied products (1992 = 100)	Oct. '18	= 184.6	Sept. '18	= 185.4	Aug. '18	= 182.8	Oct. '17	= 182.5
Productivity index, chemicals & allied products (1992 = 100)	Oct. '18	= 96.9	Sept. '18	= 97.3	Aug. '18	= 98.1	Oct. '17	= 98.5

CPI OUTPUT INDEX (2000 = 100)†

CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)



*Due to discontinuance, the Index of Industrial Activity has been replaced by the Industrial Production in Manufacturing index from the U.S. Federal Reserve Board.
†For the current month's CPI output index values, the base year was changed from 2000 to 2012
Current business indicators provided by Global Insight, Inc., Lexington, Mass.

CURRENT TRENDS

The preliminary value for the September 2018 *CE* Plant Cost Index (CEPCI; top; most recent available) increased compared to the previous month's value, continuing an upward trend that has been in place throughout 2018. The final August numbers were revised upwardly as well, because of adjustments in two quarterly reported inputs for administrative support. The Engineering & Supervision fell slightly in September, while the other three major subindexes increased. The overall CEPCI for September stands at 7.6% higher than the corresponding value from September of last year. Meanwhile, the CBI data (middle) for October 2018 show a small increase in the CPI output index from the previous month.